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Characteristics of the Integrated Steam Generators for a Liquid Metal Reactor

Yoon Sub Sim and Eui Kwang Kim
Korea Atomic Energy Research Institute
150 Deokjindong, Yuseong-gu, Daejeon 305-503, Korea
yssim@kaeri.re.kr

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Abstract

Various types of integrated steam generators, which integrate IHTS and a steam generator into a single unit of equipment for an LMR, were analyzed using an analytic solution with some simplification. The analysis showed that the undesirable reversed heat transfer, of which occurrence was previously observed only in an integrated single-region bundle type, can also occur in an integrated double-region bundle type. The mechanism of the reversed heat transfer occurrence in the double-region type is explained and it is shown the mechanism in the double-region type is completely different from that in the single-region type. Based on this finding, a method for preventing the aforementioned heat transfer is suggested. The performance of the four types of the integrated steam generators is assessed. For this assessment, a SG is actually designed for each type and the optimization in the geometric parameters and flow rate are optimized.

Key Words : LMR, SG, tube bundle configuration, integrated, separated, optimization, heat transfer

1 Introduction

An LMR(Liquid Metal reactor) can make the utilization of the uranium resource very efficient and also reduce the transuranics substantially. These desirable features make the LMR highly promising for solving the energy resource problem and the spent fuel storage problems. However, the relatively high construction cost and the concern for the possibility of the violent SWR (Sodium Water Reaction) have been the difficulties in the wide use of an LMR.

To resolve the difficulties in deploying an LMR for power generation, various efforts are being undertaken in many countries[1,2]. The efforts are generally in the direction of eliminating the intermediate heat transport system (IHTS), which is an unique system of the LMR and is conventionally required for an LMR using sodium to protect the nuclear core during an SWR event by using a coolant other than sodium or using a steam generator design which can prevent the occurrence of the SWR.

Elimination of the IHTS by using a new SG (Steam Generator) was suggested by various researchers, such as ANL[2], Kinoshita[3] and

Miyazaki[4]. Kim[5] evaluated the practicality of the suggestions and showed that their performance is not practical or they introduce new difficulties. As a way to resolve the drawbacks of the various suggestions, Sim[6] proposed integrated steam generator designs which remove the sodium-water reaction possibility by double installation of the heat transfer tube bundles in an SG. They showed the feasibility of their new designs by setting up the skeleton of the NSSS (Nuclear Steam Supply System) with the new SG designs. They subsequently analyzed the NSSS performance in a global sense by evaluating the effects of the changes in relevant system design parameters from a reference design.

The work described in this paper is a continuation of Sim[6] and analyzes the performance characteristics of the new designs in detail, concentrating on the steam generator itself. In this work, the steam generator performance is analyzed directly from the steam generator design itself without relying on the reference design. To apply this analysis method in this study, an SG was actually designed for each type and the geometric parameters and the flow rate were optimized. Using the analysis method, the effects of the tube bundle configuration on the heat transfer and pressure loss are analyzed. Also, a new configuration of the tube bundles is introduced. The performance of the various types is discussed.

2. The SG Structures for Evaluation

The integrated steam generator structures for the analysis have the following common features.

- The SG shell is filled with a medium fluid which is chemically stable with water and sodium. An alloy of lead and bismuth is used for the analysis.
- Two different kinds of heat transfer tubes are installed in the same shell. One for the heat transfer from the PHTS(Primary Heat Transport System) to the medium fluid and the other is for that from the medium fluid to the feedwater. The property related to the heat transfer PHTS-medium is denoted as PM(Primary and Medium) and that for the medium-feedwater as MH(Medium and Water) in this paper.
- The medium fluid is circulated by a pump.

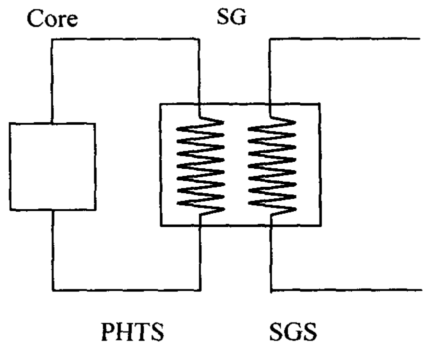


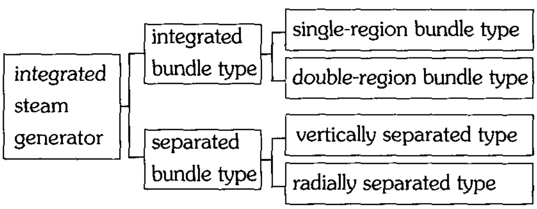
Fig. 1. The Conceptual Structure of the NSSS with the Integrated Steam Generator

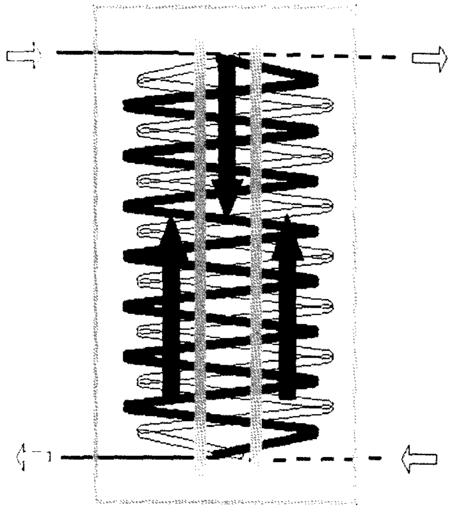
The process of the heat transfer from the PHTS to the feedwater is made inside the SG and the medium fluid works as the intermediate heat transfer fluid between the PHTS fluid and feedwater.

Figure 1 shows the conceptual structure of the NSSS using the integrated SG.

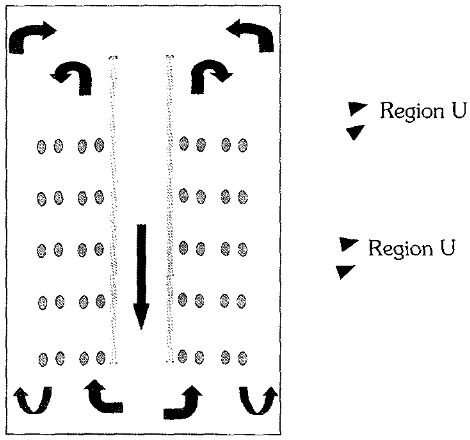
The types of the integrated steam generators studied are shown in Fig. 2.

They are referrd to as an integrated single-region bundle type, integrated double-region bundle type, vertically separated bundle type, and radially separated bundle type, respectively. The categorization of the considered steam generator types is as follows.

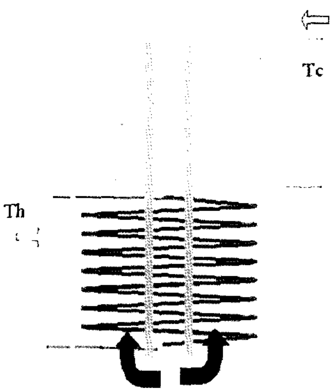




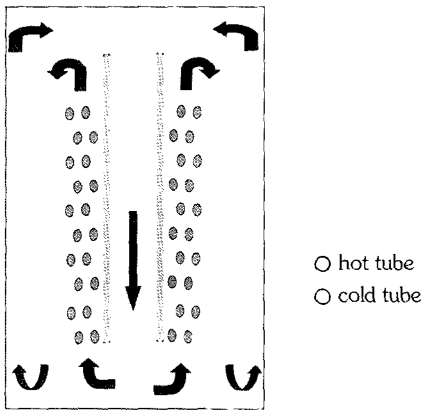
a. Integrated



b. Integrated double-region bundle typ



c. vertically separated bundle type



d. Radially separated bundle typ

Fig. 2. Heat Transfer Tube Bundle Configurations of the Integrated SG

The single-region and double-region types are categorized as integrated bundle type and the others are separated bundle type, as shown above.

In the figures, all of the tubes are helical and the colors black, white, and gray denote the type of heat transfer tubes. For example, the black and white in Fig 2.a represent a cold fluid tube and hot fluid tube, respectively. Figures 2.b and 2.d show a cross-section of the tube bundle configuration.

In the integrated configurations, the hot and cold tubes are installed alternatively and the two tubes, which are functionally different from each other, make a single integrated bundle in the space. The tubes of each type, however, construct their own tube bundle functionally. In the separated type configurations, the bundles are functionally and also physically, clearly separated. The integrated double-region bundle type of Fig. 2-b is a variation of the integrated-single-region bundle type of Fig.2-a and the bundle region is radially divided into two regions. The medium fluid flows up and down in the bundle. The radially separated bundle type of Fig. 2-d is a variation of the integrated double-region bundle type of Fig.2-b and the cold and hot fluid tubes are installed in their own radially separated regions.

The first three types were proposed in previous works[4,5,6] and the last one, i.e., the radially separated type, is newly introduced in this study.

3. Analysis Method

The analysis of the SG characteristics was conducted as follows.

3.1. Specifying the SG Design Parameters for Each Bundle Configuration

Parameters specifying the SG design such as the tube diameters, tube lengths, bundle heights, and various gap sizes were set up considering the fluid flow and heat transfer characteristics. In other Thus, a design was actually made for each configuration; this step makes the analysis method different from the previous work of Ref.[6].

3.2. Mathematical Analysis

The method in Ref.[6] was used for the heat transfer performance evaluation. The analytical solution for the condition of the uniform material property and single phase flow is used. The effects of the difference between the condition of the analytic solution and the real condition such as single-phase flow and two-phase flow were compensated for by using an average fluid property and the calibration coefficients for the overall heat transfer coefficient U. The calibration was made by comparing the analysis results to the results from a detailed analysis code for the conventional IHX and SG.

Pressure loss was calculated using the pressure loss coefficient approach. Howevers, the pressure loss for the cold fluid of the feedwater was not explicitly treated since the main portion of the required pumping power for the cold fluid is the pressure raise in the feedwater system which is not relevant to this work.

The mathematical method used in this study for the heat transfer is explained below. The original description can be found in Ref.[6], where the same nomenclature is used.

3.2.1. Integrated Bundle Type

In the integrated configuration, three fluids are involved in the heat transfer simultaneously and the heat transfer is expressed by Eqs. (1)~(3) when the fluid properties are treated as uniform.

$$\frac{dT_P}{dx} = a(T_P - T_M), \qquad a = \frac{-UA_{PM}}{(mCp)_P} \tag{1}$$

$$\frac{dT_H}{dx} = b(T_M - T_H), \qquad b = \frac{-UA_{MH}}{(mCp)_H} \tag{2}$$

$$\frac{dT_M}{dx} = c(T_P - T_M) - d(T_M - T_H),$$

$$c = \frac{UA_{PM}}{(mCp)_M}, \; d = \frac{UA_{MH}}{(mCp)_M}, \; x = \frac{s}{L} \tag{3}$$

where s is the vertical direction coordinate in the bundles and x=0 and x=L are, respectively, the bottom and the top of the tube bundle region. In the equations, the temperatures T_P, T_M ,and T_H represent the PHTS(hot), medium, and water/steam(cold) temperatures, respectively. Equations (1), (2), and (3) are for the energy balance in the PHTS(hot), water/steam (cold), and medium fluids, respectively.

The solution to the set of governing equations is found with the appropriate boundary conditions at each fluid inlet and the solution is shown below.

$$T_P(x) = C_1 - \frac{a}{\alpha - a} C_2 e^{\alpha x} - \frac{a}{\beta - a} C_3 e^{\beta x} \quad (4)$$

$$T_M(x) = C_1 + C_2 e^{\alpha x} + C_3 e^{\beta x} \quad (5)$$

$$T_H(x) = C_1 + \frac{b}{\alpha + b} C_2 e^{\alpha x} + \frac{b}{\beta + b} C_3 e^{\beta x} \quad (6)$$

where the constants C, α, and β are determined from the SG operation conditions such as *UA*, flow rate, and inlet conditions.

- Boundary condition for the integrated single-region bundle configuration.

$$T_M(s=0) = T_M(s=L) \quad (7)$$

- Integrated double-region bundle configuration.

$$T_M^U(s=0) = T_M^D(s=0) \quad (8)$$

$$T_M^U(s=L) = T_M^D(s=L) \quad (9)$$

3.2.2. Separated Bundle Type

In the separated type, the system can be considered as a serial coupling of the PHTS-Medium heat transfer and Medium-Feedwater heat transfer. The heat transfer can be described by the equations for a counter-flow heat exchanger when the fluid property is considered uniform. The exit temperatures are expressed by Eq. (10) and (11) of a counter-flow heat exchanger.

$$T_c(L) = T_c(0) + (T_h(L) - T_c(0)) \left(\frac{1 - \exp(-a_h(1 + R_{mc}^{HC}))}{1 + \exp(-a_h(1 + R_{mc}^{HC}))/R_{mc}^{HC}} \equiv \eta_{Mc} \right) \quad (10)$$

$$T_h(0) = T_c(0) + (T_h(L) - T_c(0)) \left(\frac{1 + 1/R_{mc}^{HC}}{1 + \exp(-a_h(1 + R_{mc}^{HC}))/R_{mc}^{HC}} \equiv \eta_{Mh} \right) \quad (11)$$

where the cold and hot fluids enter the heat exchanger, respectively, at $s=0$ and L. When a fluid flows in the same direction as that of the feedwater, its flow rate becomes positive. a_h is the a of Eq. (1) calculated for the hot fluid and R_{mc}^{HC} is defined by the following equation.

$$R_{mc}^{HC} = \frac{(\dot{m} C_p)_{hot\ fluid}}{(\dot{m} C_p)_{cold\ fluid}} \quad (12)$$

Where the hot and cold fluids have a relative meaning and the actual fluids corresponding to the hot and cold fluids depend on the configuration when Eq.(12) is applied.

- Boundary condition

From the configuration, the medium fluid temperature at $s=L$ in the heat transfer with the PHTS fluid, $T_c^{PM}(L)$ is the same as that at $s=0$ in the heat transfer with the feedwater fluid, $T_h^{MH}(0)$.

$$T_c^{PM}(L) = T_h^{MH}(0) \quad (13)$$

From Eqs. (10),(11), and (13), the cold temperature of the medium fluid T_{Mc}, which is the temperature when the medium fluid leaves the MH region and enters the PM region, is calculated by Eq. (14).

$$T_{Mc} = \frac{T_{Hc} + (T_{Ph}\eta_{Mh} - T_{Hc})\eta_{Mc}}{1 - \eta_{Mc} + \eta_{Mh}\eta_{Mc}} \quad (14)$$

where T_{ph} and T_{hc} correspond to the inlet temperatures of the PHTS and feedwater fluids, respectively.

3.2.3. Calibration of the Analysis Method

In using the analysis model, some errors are involved such as the error from the non-uniformity of the fluid property and the existence of the saturation region in the water. To compensate for the error effects, the analysis model was applied to the reference design which will be explained in the next section and the calibration factors that make the IHTS cold and steam temperatures from the analysis model equal to the values of the reference design were found. Since the reference design values were determined by the SG analysis code HSGSA[7], which fully considers the non-uniformity of the fluid property and the existence of the saturation region, the error effects can be compensated for by calibrating the model of this study to the reference design analysis with the use of the calibration factors. The calibration factors that calibrate the values of UA determined from the heat transfer rate and log-mean temperature difference are as follows.

- For UA_{ihx} : 0.76
- For UA_{sg}/ UA_{ihx} : 1/0.73

3.2.4. Reliability Evaluation of the Analysis Method

The sources of the possible errors in the described analysis method are categorized into two groups. One is the errors from the simplification and the other is those induced in the process of deriving and applying the solution. An evaluation was made for each category.

- Checking for the possible error in the process of deriving and applying the solution:
  - The physical validity of the temperature profile from the calculated results was checked and no abnormality was observed.
  - The energy balance among the three fluids was checked and the error in the balance was always less than $10^{-12}\%$.
- Checking the magnitude of the error from the simplification in modeling the governing equations:
  - The calculated heat transfer rates were compared to the results from the quite recent analysis which considered the variation of the fluid material property, convective heat transfer coefficient, and phase change in the feedwater side with the use of the LMR SG analysis code HSGSA[7]. The comparison was made directly to the integrated steam generator designs of this study, while the method calibration was made from the analysis data for the conventional LMR NSSS structure. In the comparison, the difference in the total heat transfer rates was less than 3% for the four types of the steam generators respectivy at the test conditions which corresponds to an optimum design condition of each type such as that shown in Table 4. The temperature distribution of the water/steam was obviously quite different for each design, as was expected. The overall distributions of the three fluids was, however, similar and the heat transfer characteristics were correctly shown without distortion by the analysis method of this study.

From these assessments, the analysis method is evaluated to be quite reliable for the purpose of this study.

4. Temperature Distribution

The analysis model described in the previous section was applied to the integrated SG designs,taking the operation condition of KALIMER [8] as the reference condition of the analysis. The IHTS fluid of KALIMER, i,e., sodium, corresponds to the medium fluid of this study in its function.

Figures 3 and 4 show the calculated temperature distributions of the single-region and double-region bundle types, respectively. Among the cases shown in the figures, only the flow rates of the medium fluid are different from each other and the other parameters are kept the same in the calculation condition. In Fig. 4, there are two groups of figures

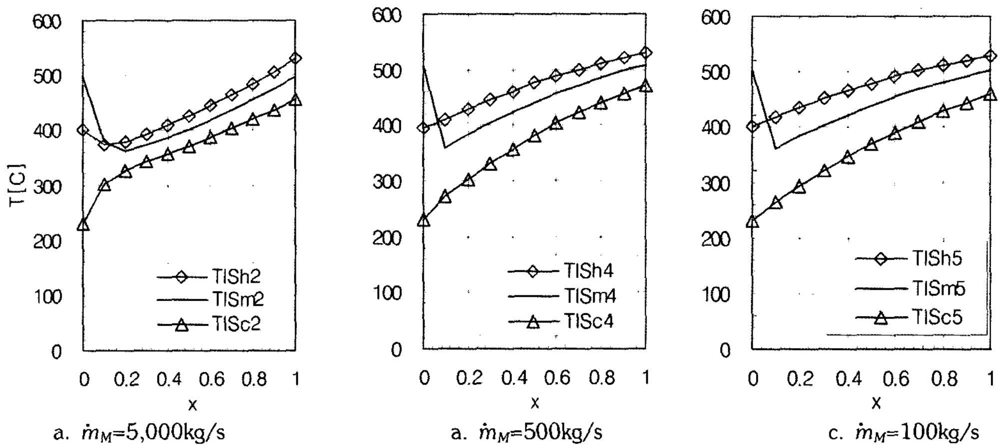


Fig. 3. Temperature Distribution in the Integrated Single-region Bundle Type

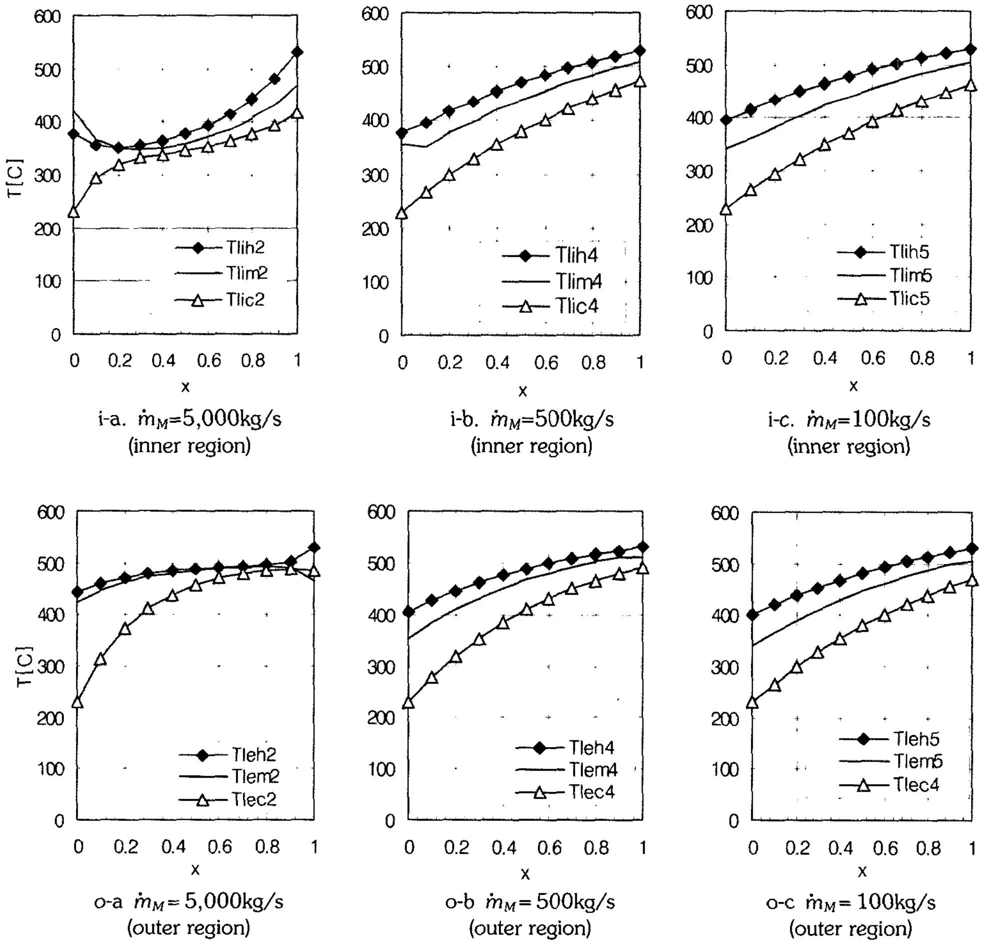


Fig. 4. Temperature Distribution in the Integrated Double-region Bundle Type

Table 1. Flow Directions in Figures 4 and 5

		hot fluid	medium fluid	cold fluid	direction
single-region type		-	+	+	+: from x/L=0 to 1 -: from x/L=1 to 0
double-region type	inner region	-	+	+	
	outer region	-	-	+	

since the double-region type has two different bundle regions, i.e., inner and outer regions. The flow directions are presented in Table 1. The letters *h*, *m*, and *c* in the figure index imply hot (PHTS sodium), medium, and cold (water /steam) fluids, respectively. Also, in the index, *TI* represents temperature of the integrated type, and *S*, *i* , and *e* respectively represent the single-region type, internal region, and external region.

The integrated single-region type has, as shown in Fig. 3, a unique temperature distribution, where the medium fluid temperature is higher than the hot fluid temperature in a certain region. This distribution makes the heat transfer less efficient. A bundle configuration of the integrated double-region type was proposed to cure the undesirable distribution[6]. If the distributions for the medium fluid flow rate $\dot{m}_M$ of 100kg/s are compared for the two configuration types we see that, the undesirable disappeared feature in the single-region type is completely disappeared in the double-region type. When the flow rate is increased to 500kg/s, however, the double-region distribution shows the undesirable distribution symptom slightly in the medium fluid entrance region (x/L~0) and the distribution becomes apparently undesirable in the entrance region as the flow rate is increased further to 5,000kg/s. These results show that making the medium fluid flow upward and downward through the bundle cures the undesirable feature in the temperature distribution somewhat but not completely.

The reason for the occurrence of the undesirable distribution in the single-region comes from the requirement that the medium temperatures at its inlet and outlet regions should be the same. While, there is no such requirement in the double-region type but this type is not completely free from the undesirable distribution either. This issue is investigated by analyzing the temperature distribution formation factors in the double-region type.

In the double-region type, the medium fluid is involved in the heat transfer in two modes. One is that the fluid carries the heat taken from one region to the other region, which is the way of the medium fluid involvement in a separated configuration such as the vertically separated configuration type of Fig. 2.C. This mode of heat transfer is called the bulk transfer hereafter. The other is that the fluid works as an intermediate heat transfer path between the hot and cold fluids in the same region such as heat transfer tube wall does, and is called the local transfer hereafter.

As the medium fluid flow rate decreases, the local transfer becomes relatively more enhanced and the bulk transfer is reduced. When the medium flow rate decreases further to zero, the fluid acts as if it is a solid and its temperature becomes a middle value of the hot and cold fluid temperatures, and its distribution becomes similar to a wall temperature distribution.

When the flow rate increases, the bulk transfer becomes dominant and the temperature distribution basically follows that in a conventional heat exchanger of two fluids. Based on this, the fluid temperature distribution in the integrated SG at a high medium flow rate condition, where the

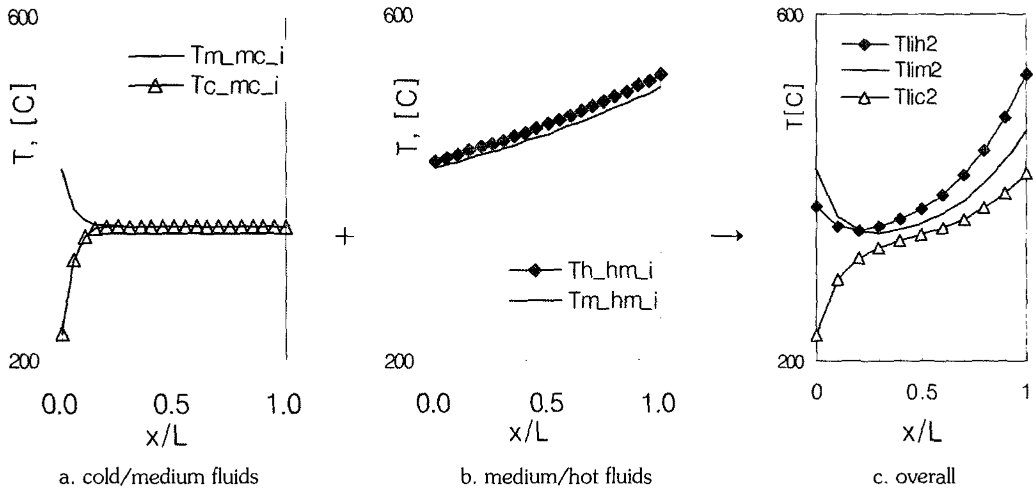


Fig. 5. Decomposition of the Temperature Distribution of the Double-region Bundle Type (inner region)

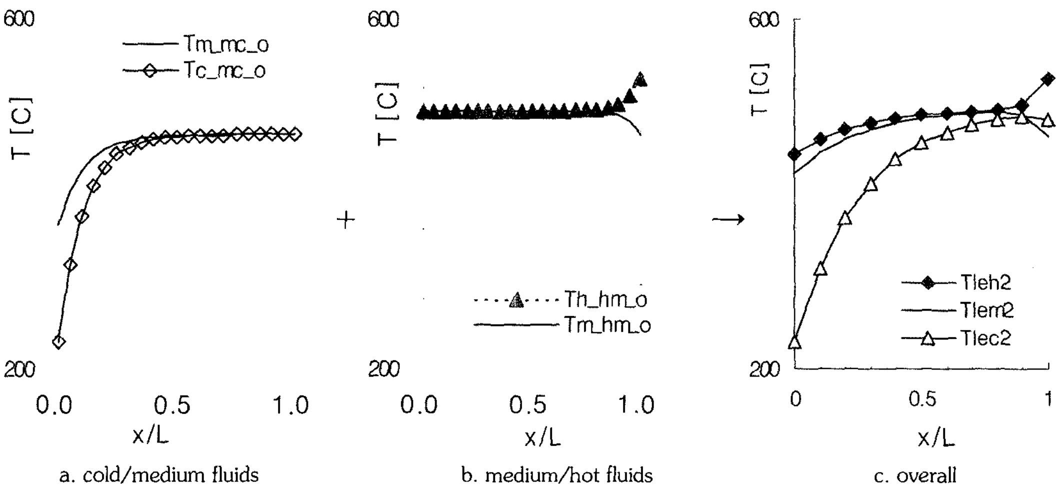


Fig. 6. Decomposition of the Temperature Distribution of the Double-region Type (outer region)

undesirable distribution occurs, can be decomposed into the one formed from the relation between the hot and medium fluids and that between the medium and cold fluids, as shown in Figs. 5 and 6.

In a two-fluid heat exchanger, the relative slopes of the temperature distribution curves are determined by the ratio of $\dot{m}C_p$, that is, R^{HC}_{mc}, which can be inferred from Eqs. (10) and (11). Also the inlet temperature of the fluid with the larger $\dot{m}C_p$, maximum fluid hereafter, is extended longer compared to the fluid with the smaller $\dot{m}C_p$, minimum fluid hereafter, in a counterflow condition. The values of R^{HC}_{mc} for the cases of Fig. 4 are listed in Table 2. Also, the overall heat transfer coefficients are listed in Table 3.

In Tables 2 and 3, the subscripts h, m, and c denote hot, medium, and cold fluids, respectively,

Table 2. Values of R_{mc}^{HC} for the Cases in Figure 4

case		a	b	c
medium flow rate, kg/s		5,000	500	100
inner region	mCp_h/mCp_m	-0.9	-9.3	-46.7
(Fig. 4-i)	mCp_m/mCp_c	1.9	0.2	0.04
outer region	mCp_h/mCp_m	0.8	7.8	39.0
(Fig. 4-o)	mCp_m/mCp_c	-2.3	-0.2	-0.05

Table 3. Values of *UA* for the Cases in Figure 4

Unit : MW/℃

case		a	b	c
medium flow rate, kg/s		5,000	500	100
inner region	UA_{hm}	6.66	3.58	2.58
(Fig. 4-i)	UA_{mc}	2.22	1.72	1.45
outer region	UA_{hm}	5.86	3.17	2.23
(Fig. 4-o)	UA_{mc}	1.87	1.47	1.22

and a negative value in R_{mc}^{HC} means the flow directions are opposite between the hot and cold side flows since the sign of the flow rate follows the convention used in Table 1.

For the decomposition of the distributions in Figs. 4 i-a and o-a, the temperature distribution is calculated when only two fluids are involved in the heat transfer, and the results are shown in Figs. 5 and 6. Regarding the distribution in the inner region of Fig. 5, first the heat transfer between the cold and medium fluids (Fig. 5-a) is discussed for the decomposition of the distribution. Since their flow directions are parallel to each other and their UA is large, the two fluid temperatures approach each other and become the same value. The cold fluid is the minimum fluid and is subject to a gets a larger temperature change. These features make the distribution similar to that of Fig. 5-a.

Between the medium and hot fluids, their flow directions are opposite to each other and the medium fluid is the maximum fluid with a slight difference in $\dot{m}C_p$. From this, the temperature curves become nearly parallel with a slightly downward convex shape. The distribution in the three fluids is a combination of the distributions in the two-fluid cases. The temperature curves of the medium and cold fluids come to have a substantial change from the distribution of Fig. 5-a by the combination near their outlets, i.e., x/L~1. The hot fluid which enters at x/L=1 comes to have a decreases more rapidly near its inlet region compared to the distribution of Fig.5-b, because of the temperature decrease of the medium fluid. Since the UA between the hot and medium fluids is large, the hot fluid continues its decrease further and eventually its temperature becomes the same as the medium fluid temperature. As x/L decreases from this location, the medium fluid temperature rapidly approaches its inlet temperature, i.e., it increases rapidly, and the hot fluid temperature comes to follow the medium temperature rise, i.e., the undesirable reverse heat transfer from the medium fluid to the hot fluid occurs.

Figure 6 shows the decomposition of the distribution in the outer region, Fig. 4o-a.

Compared to the inner region condition, the medium fluid enters from the top, i.e., x/L=1 and the flow direction configuration becomes the opposite of that of the inner region. The cold fluid flows in an opposite direction to the medium fluid and the hot fluid flows parallel to the medium fluid. However, the basic physics involved is the same as that in the inner region and the temperature distribution characteristics can be explained by the same physics as those for the inner region.

From this discussion, it is deduced that the undesirable reverse heat transfer occurs when the flow direction configuration is a combination of parallel and opposite flows and the overall heat transfer coefficients are high. This suggests that configuring the flow directions only in the opposite directions, i.e., a conterflow configuration, will remove the possibility of the occurrence of the reverse heat transfer and improve the heat transfer performance. The configuration of the radially separated type shown in Fig. 2d consists only of counterflows. In terms of heat transfer, the radially separated type is similar to the vertically separated type in Fig. 2c. Also, the undesirable temperature distribution can be eliminated when the overall heat transfer coefficient is small.

5. Evaluation of the Performance

The performance was evaluated for the integrated steam generator types shown in Fig. 2 and they are compared at their optimum design conditions.

The relationship between the heat transfer rate and medium flow rate was investigated by changing the medium flow rate while the other parameters were kept the same. The results are shown in Fig. 7, where Qid, Qis, and Qsr respectively denote the heat transfer rate of the double-region type, single-region type, and radially separated type.

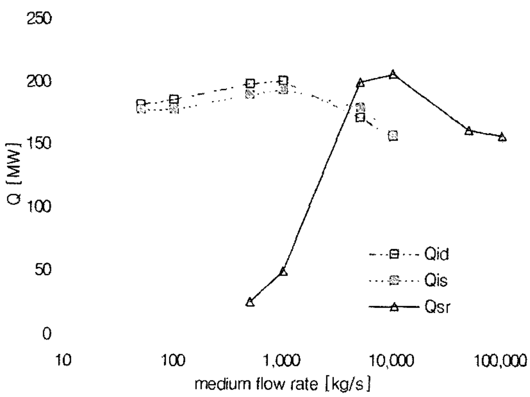


Fig. 7. Medium Flow Rate and Heat Transfer Rate

The figure there is an optimum medium flow rate for each configuration, although a higher flow rate yields a higher convection heat transfer coefficient. The optimum flow rate of the separated type is about 10 times larger than that of the integrated type. Also, the effect of the medium flow rate change is relatively small in the integrated bundle types while it is very large in the separated type. These features come from the fact that the integrated bundle type has the heat transfer modes of the local transfer as well as the bulk transfer, while the separated type only has the bulk transfer mode, as explained previously. This means the integrated bundle types can be operated at a much smaller medium fluid flow rate than the separated bundle types. This feature can be very important. The medium fluid needs to be a substance which is chemically stable with sodium and water, and currently the most promising candidate is the alloy of lead and bismuth. However, the density of Pb-Bi is very large and it can generate a high mechanical load to structures at the same fluid velocity and a severe restriction can be imposed on the medium fluid flow rate. Also,the insensitivity of the integrated type suggests that a sufficient heat transfer may be achieved even when the pumping for the medium

Table 4. The Optimized Design and Performance of the Integrated SG Concepts

	Integrated Single-Region Type	Integrated Double-Region Type	Radially Separated Type	Vertically Separated Type
hot tube OD, m	0.025	0.025	0.025	0.025
cold tube OD, m	0.025	0.025	0.025	0.025
hot tube t, m	0.0008	0.0008	0.0008	0.0008
cold tube t, m	0.003	0.003	0.003	0.003
hot tube length, m	50.0	43.0	28.0	28.0
cold tube length, m	50.0	43.0	48.0	48.0
hot bundle height, m	8.9	13.1	11.0	10.0
cold bundle height, m	8.9	13.1	11.0	11.0
bundle region height, m	**8.9**	**13.1**	**11.0**	**21.0**
hot tube Pitch/OD, (R-plane)	1.5	1.5	1.5	1.5
cold tube Pitch/OD, (R-plane)	1.5	1.5	1.5	1.5
# of tube rows,inner	33	15	11	hot:12
# of tube rows,outer	-	7	6	cold:11
# of hot tubes	416	365	322	330
# of cold tubes	415	360	174	184
# of tubes	831	725	496	514
# tubes.inner/#tuebs.outer	-	0.55	0.65	-
shell ID,m	**2.96**	**2.34**	**1.96**	**1.38**
shell volume(bundle region), m^3	**61.2**	**56.1**	**33.2**	**31.5**
Vol, med. fluid, m^3	41	40	24	22
total fluid mass, ton	356	347	208	194
total mass(bundle region), ton	401	388	232	216
heat transfer area,total, m^2	3,200	2,448	1,364	1,419
medium flow rate, kg/s	1,210	1,100	6,500	6,500
Q: heat transfer rate, MW	**200.0**	**200.1**	**199.9**	**200.1**
Q/Vol.shell(Bundle), MW/m^3	**3.27**	**3.56**	**6.02**	**6.34**
medium fluid P loss, KPa	8.0	13	565	402
pumping power, hot,kw	775	845	691	661
pumping power, medium,kw	1.1	1.7	432	308
fluid Vel. medium, m/s	0.05	0.16	1.45	1.30
$A/A_{radially\ separated}$	**1.74**	**1.33**	**1.00**	**1.04**
$Vol/Vol_{radially\ separated}$	**1.42**	**1.30**	**1.00**	**0.95**

fluid is lost by an accident.

The optimum design was sought for each configuration type with the condition of a heat transfer rate of 200MW and the system operation condition which came from the reference system design of Ref. 7.The operation condition are described below.

- hot fluid
  - fluid: sodium - inlet temperature : 530.0℃
  - flow rate : 1,071.5 kg/s
- cold fluid
  - fluid: water - inlet temperature : 230.0℃

- flow rate : 87.725 kg/s

The optimization target used was to have a smaller bundle volume and pumping power. The geometric parameters of the tubes and bundles, and the medium fluid flow rate were changed so that the optimization target was achieved. Table 4 shows the results.

As shown in the table, each type has its own optimum design and the differences in the designs are relatively small between the integrated bundle types and between the separated bundle types, but are large between the integrated and separated types because of the difference in their heat transfer physics.

When the heat transfer efficiency is compared by the ratio of the heat transfer ratio to the required volume, the separated bundle types are much more efficient than the integrated bundle types. The efficiency is about 6 MW/m^3 for the separated types and about 3.5 MW/m^3 for the integrated types. The difference between the vertically and radially separated types is considered to be mainly due to the fact that the radially separated type considered all the spaces required for manufacturing and operation while the vertically separated type did not consider the space between the upper bundle and lower bundle, which is required for installing the tube sheets and nozzles, and can change significantly depending on the manufacturing method.

The efficiency difference between the single-region and double-region is somewhat small, though the double-region has a slightly better performance. This feature is considered to have come from the fact that the double-region type requires more spaces than the single-region type, since its flow path is more complex. Also, from Table 4, the ratio of the required heat transfer area for the single-region type to that for the double-region type is 1.74/1.33=1.31 and that of the required volume is 1.42/1.30=1.09, which is smaller than the area ratio. This means the use of the volume in the double-region type is less efficient and the double type suffers from the geometric complexity compared to the single type. However, the difference in the efficiency between the two types can be increased further when the SG operation condition is changed to the region where the sensitivity of the heat transfer rate to the change of the overall heat transfer coefficient is large. This is because the operation condition, which is the condition of the reference system design, is at the point where the sensitivity is relatively small. Also, there is a possibility of having a better performance for the double-region type in a design with well tuned overall heat transfer coefficient values and flow rates, since the undesirable reverse heat transfer is inherently present in the single-region type but it is not so in the double-region type.

The pumping power and the velocity of the medium fluid are quite large in the separated types. The high flow rate of 6,500kg/sec results from the high density of lead-bismuth. When the flow rate in mass is converted to that in volume, the rate becomes approximately 0.77m^3/s and its magnitude is within the range of the values for the main coolant pumps in nuclear plants. Actually the flow rate per pump in BREST-300 which uses lead-bismuth as the main coolant is 10,000kg/sec[9]. Thus the high flow rate of 6,500kg/sec is basically an achievable value.

Reference 6 showed the large pumping power for the separated types is compensated for by thier better heat transfer performance in the plant cycle efficiency effects. The large medium fluid velocity, however, is another matter and can be a difficulty in an actual use because of the reason discussed in the section of the temperature distribution. Though the required volume for the bundle region of the integrated type is about 1.7 times larger than that for the separated type, this difference will be substantially decreased when the final volume of an SG assembly, which includes the spaces for installing tube sheets, nozzles, and a motor for the medium fluid pump, is compared. Also, an electro-magnetic pump can be used for the integrated type since the required flow rate is very small for that type. An electro-magnetic pump can be installed inside the SG shell and it will decrease the required total space volume for an SG assembly considerably compared to the case when a mechanical pump is installed outside the SG shell. It means that there is still a possibility that the integrated double-region type can be the best choice when the medium fluid velocity is required to be small for the fluid-structure interaction though the separated bundle types have better heat transfer performance.

Also the results in Table 4 show that the analysis approach of Ref. 6 estimating the overall performance of a SG design without designing the SG but utilizing the parameter sensitivities are valid. The results of Ref. 6 are close, in the comparative overall performance of the SG design types, to the results of this study which were produced by actual designing the SG.

6 Conclusions

Various types of the integrated steam generator design concepts were analyzed for their performance characteristics by actually designing a steam generator for each type, the major results from the analyses are as follows.

- The possibility for the occurrence of the undesirable reverse heat transfer also in the integrated double-region bundle type was confirmed and the mechanism of the occurrence was explained. Also, a method for preventing its occurrence was suggested.
- The separated bundle types have the best heat transfer efficiency among the various integrated SG types in terms of the ratio of the heat transfer rate to the required bundle region volume. Their values are about 1.7 times larger than those of the integrated bundle types at the reference system operation conditions.
- Though the separated bundle types have a better heat transfer performance, there is still a possibility that the integrated double-region type can be the best choice when the medium fluid velocity is required to be small for the fluid-structure interaction.

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Nomenclature

A	area, flow or heat transfer
Cp	specific heat
D	diameter, region of downward fluid flow
H	feedwater/steam
L	bundle length
$\dot{m}$	flow rate
P	PHTS
s	vertical direction coordinate in the bundles
T	temperature
U	overall heat transfer coefficient
x	non-dimensionalized s

Greek Letters

η	coefficient in the temperature equations (10) and (11)

Superscripts and Subscripts

c	cold
H	feedwater/steam
h	hot
i	internal of the tube

M	medium fluid
MH	medium-water/steam
P	PHTS
PM	PHTS-medium

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