The prevention of leakage flows of coolant gas is important for a thermal hydraulic design of HTGR core which consists of prismatic graphite blocks. In particular, a seal mechanism for the core support blocks is necessary because gaps between core support blocks induce leakage flows in the core. Here, a seal mechanism, which consists of graphite seal element with triangular cross section and V-shaped seal seat, has been proposed. Air flow experiments were conducted to study the leakage flow characteristics of this seal mechanism. It is shown that the present seal mechanism is highly effective in preventing leakage flows as compared with the plate-type seal mechanism. It is also found that most of the leakage flow occurs at the seal element end-gaps and the pressure loss coefficient factor of this seal mechanism can be predicted with the use of the effective flow area of the end-gaps.

KEYWORDS : graphite seal element, seal mechanism, HTGR type reactors, core support block, leakage flow, air flow experiment, coolant gases

I. INTRODUCTION

In an HTGR core consisting of graphite blocks, leakage flows of coolant gas occur at the gaps between blocks. These leakage flows create unfavorable thermal hydraulic effects in the core, such as excess fuel temperature and the increase of the thermal stress in the graphite blocks. These effects are particularly significant in the high temperature operation (reactor outlet temperature nearly 950°C) of the reactor.

Prismatic graphite blocks in an HTGR core are supported by the large hexagonal core support blocks. The gaps on the order of 2 mm exist between the core support blocks during the reactor operation. Since these gaps induce leakage flows in the core, a seal mechanism for the gaps between the core support blocks is necessary. A general concept of a seal mechanism is shown in Fig. 1; graphite seal elements are placed on the peripheries of the core support blocks to seal the gaps between blocks. In the course of a design of High Temperature Engineering Test Reactor (HTTR), which has been developed by the Japan Atomic Energy Research Institute (JAERI), a plate-type seal mechanism has been devised and its leakage flow features have been studied(1)(2). Although the plate-type seal mechanism is mostly effective in preventing the leakage flow, it is vulnerable to the wedge-shaped type relative displacements of the core support blocks. Also, the pressure loss coefficient factor changes in a wide range depending on the shape of the relative displacements. It is required in the HTTR design that the pressure loss coefficient factor of the seal mechanism be high and stable under various conditions of core support block.

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relative displacements. We propose a new seal mechanism, which is effective in preventing leakage flows for various block configurations. This seal mechanism consists of graphite seal element with triangular cross section and the V-shaped seal seat, as shown in Fig. 1. Air flow experiments using the modeled core support blocks were carried out to study its leakage flow characteristics for various block configurations. It is found that this seal mechanism decreases greatly the leakage flow as compared with the plate-type seal mechanism and gives very stable leakage flow characteristics for various block relative displacements.

II. EXPERIMENTAL METHOD

The graphite seal element and the modeled core support blocks are shown in Fig. 2 (a)~(c). The material of the test block and the seal elements was IG-11 (Toyo Tanso Co.), a very fine grained
graphite made by isostatic molding. The seal elements with three different types of cross sections (type I ($\alpha = 90^\circ$), type II ($\alpha = 70^\circ$) and type III ($\alpha = 110^\circ$)) were used in the experiments. The lengths of the seal seat and the seal element were 200 and 198 mm, respectively. When the seal element was set on the block, the seal element end-gaps were created at both ends of the seal element, as shown in Fig. 2(a), (b). Here, we adopted the simple shape of seal element end-gap to study the basic leakage flow characteristics. The test block was connected to a blower inlet through a duct equipped with laminar flow meters. The gap width $\delta_g$ between the test blocks and the seal element end-gap width $\delta_s$ were basically set equal to 2 and 1 mm, respectively. The effect of the end-gap width on the pressure loss coefficient factor was studied by setting one end-gap at the center of the seal seat. The experiments were carried out by varying $\delta_s$. 

Fig. 2 (b) Plant view of seal element

Fig. 2 (c) Side view of seal element

Fig. 3 Assumed relative block displacements drawn are exaggerated in this figure.

Fig. 3 Assumed relative block displacements
from 1 to 3 mm and \( \delta_b \) from 2 to 4 mm. Pressure measuring holes were drilled in one of the model blocks and the pressure difference with reference to the atmospheric pressure was measured by a digital pressure differential gage. The pressures from all the holes were monitored during the experiments. It was confirmed in the experiments that the pressures measured at these holes were almost the same. The various relative displacements of the core support blocks due to the temperature distribution of the bottom core were assumed in the experiments. There are parallel and wedge-shaped (types A and B) relative displacements of the blocks, as shown Fig. 3. These block relative displacements are assumed to occur in the reactor due to the temperature distribution. In the experiments, air at room temperature and atmospheric pressure was used as a working fluid and a leakage flow rate \( M(\text{kg/s}) \) was measured as a function of a pressure drop \( \Delta p(\text{Pa}) \).

### III. EXPERIMENTAL RESULTS

The experimental data were represented by the pressure loss coefficient factor \( A = \frac{2 \rho \Delta p}{M^2} \) (m\(^{-4}\)) vs. the Reynolds number \( Re = \frac{4M}{\mu L} \) relation\(^{(1)(2)}\). Here, \( \rho \), \( \mu \), and \( L \) denote the density, the viscosity of the gas and the wetted perimeter of the gap between the core support blocks. Figure 4 shows the experimental results of the type I(\( \alpha = 90^\circ \)) graphite seal element for three different block configurations. It is found that the pressure loss coefficient factor for this seal mechanism remains almost constant for various relative displacements. This result is noteworthy as compared with the results of the plate-type seal mechanism\(^{(2)}\). It is also seen in Fig. 4 that \( A \) is almost constant, independent of the Reynolds number. Even when a wedge-shaped level displacement is created between blocks, the graphite seal element slides on the seal seat and adjusts itself to a new position so that the gap between the seal element and the seal seat is kept small in this seal mechanism. The gap width between the seal element and the seal seat is estimated to be equal to the equivalent gap width (\( \sim 15 \mu \text{m} \)), which is an order of the surface roughness of the graphite seal element, between contacting graphite blocks\(^{(3)}\). The leakage flow rate evaluated using this equivalent gap width is small as compared with the experimental data. Thus, most of the leakage flow in this seal mechanism occurs at the seal element end-gaps.

#### Figure 4

\( A \) vs. \( Re \) relation for type I model

\( (\delta_a = 1.15 \text{ mm} \times 2), \delta_b = 2.0 \text{ mm} \)

Figure 5 (a), (b) shows \( A \cdot Re \) relation for the types II and III graphite seal elements. With the comparison of these data, it is seen that the type III seal element, which is more like the plate-type seal element\(^{(1)(2)}\), gives the highest pressure loss coefficient factor. However, the
reduction of $A$ is the largest with the change of the block configuration. This trend coincides with the results of the plate-type seal elements, although the decrease of $A$ for the present seal mechanism is a factor of 2. It is also found from Fig. 5(a) that $A$ for the seal element with a sharper vertical angle (type II, $\alpha = 70^\circ$) tends to be the most stable for various blocks configurations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{(a) $A$ vs. $Re$ relation for types II and III model}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6.png}
\caption{Comparison of $A$ for present seal mechanism with that for plate-type seal mechanism}
\end{figure}
Since most of the leakage flow occurs at the seal element end-gaps, the pressure loss coefficient factor can be determined by the local block displacements at the ends of the seal element. The block displacements for the types A and B are regarded as the same at the ends of the seal element and correspond locally to the parallel (2 mm) block displacement. In Fig. 4, it is seen that the data of the parallel block displacement are very close to those of the type B wedge-shaped displacement. However, the data of type A are somewhat larger than the above two data, because, in type A block displacement, the seal element is somewhat slanted and this decreases the seal element end-gap width.

IV. Discussion

The leakage flow characteristics for the present seal mechanism (type I, \( \alpha = 90^\circ \)) are compared with those for the plate-type seal mechanism under the same conditions of the relative block displacements in Fig. 6. Here, seal elements with the length of 198 mm were used so that there are 1 mm gaps at both ends of the seal element. The block relative displacements were equally set for both types of seal elements. The results clearly show that the present seal mechanism gives a high and stable pressure loss coefficient factor for various relative block displacements.

In chap. III, it was found that the leakage flow through this seal mechanism mostly occurs at the seal element end-gaps. Since the pressure loss coefficient factor \( A \) is almost independent of \( Re \) as seen in Fig. 4, we assume that the leakage flow rate is determined by the area \( A = \delta_b \times \delta_s \) of the seal element end-gap. When there is no level displacement between blocks, the dimensionless pressure loss coefficient factor \( K = A \times A^2 \) is calculated for various combinations of \( \delta_b \) and \( \delta_s \) and is shown in Fig. 7. In this experiment, two end-gaps were
set at both ends of the seal element. It is seen that the dimensionless pressure loss coefficient factor $K$ approximately equals to unity, except when $\delta_s = 0.12$ mm. This means that the leakage flow is determined by the area $A$. In the case when $\delta_s$ is less than 1 mm (symbols $\triangle$, $\bullet$ in Fig. 7), the values of $K$ are slightly less than the other data. The decrease of $K$ below 1.0 is due to the effect of the leakage flow through the contacting graphite surfaces between the seal element and the seal seat. As $\delta_s$ approaches to zero, as in the case for $\delta_s = 0.12$ mm, most of the leakage flow is dominated by this effect. However, the pressure loss coefficient factor $A$ becomes so large in this region that the effect of the leakage flow through contacting graphite surfaces on a thermal hydraulic calculation in a reactor is small.

On the other hand, when there is a parallel level displacement between blocks, the block gap width, which determines the leakage flow, becomes wider as is seen in Fig. 8. It is predicted that there is some effective gap width $\delta_b$, or the effective flow area $\tilde{A}$ ($= \delta_b \times \delta_s$), which reduces the dimensionless pressure loss coefficient factor to near 1.0. Various effective gaps are examined.

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**Fig. 8** Side view of seal mechanism in presence of parallel level displacement

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**Fig. 9** Dimensionless pressure loss coefficient factor using effective flow area for parallel level displacement

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One seal element end-gap is set at the center of the seal seat.
and $\delta_s$ defined in Fig. 8 is found to be appropriate for the effective flow area $\tilde{A}$. With the use of this effective flow area $\tilde{A}$, the data for the parallel level displacement can be summarized in the same way as those for no level displacement. The results for the various combinations of three parameters ($\delta_s$, $\delta_b$ and the block level displacement) are shown in Fig. 9. It is seen that the values of the dimensionless pressure loss coefficient factor $K = \tilde{A} / A^2$ for $\delta_s = 2, 3$ mm are almost the same, while the data for $\delta_s = 1$ mm are slightly less than the other data. It is also seen that a scatter of data is larger for the case $\delta_s = 1$ mm as compared with the other cases and the values of $K$ tend to be smaller with decreasing the effective flow area of the end-gap. This scatter is due to the effect of the leakage flow through the contacting graphite surfaces between the seal element and the seal seat, as mentioned above. The mean values of $K$ for $\delta_s = 1$ mm and $\delta_s = 2$, $3$ mm are 0.998 and 1.26, respectively. Thus, with this effective flow area $\tilde{A}$ and the mean values of $K$, pressure loss coefficient factor $\tilde{A} = K / A^2$ can be predicted for various block displacements.

V. CONCLUSION

A seal mechanism has been proposed to prevent the leakage flows through the gaps between core support blocks in an HTGR. Air flow experiments show that this seal mechanism is highly effective in preventing leakage flows for various relative displacements of core support blocks. It is found that most of the leakage flow occurs at the seal element end-gap and the pressure loss coefficient factor for various block configurations can be predicted with the use of the effective flow area of the seal element end-gap.

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