Sealing analysis for nuclear vessel of PWR

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1 INTRODUCTION

Although design by analysis of pressure vessel has become a requirement in all codes for more than 20 years, sealing design for nuclear components is still too complicated and there are yet no criteria about this aspect, even though in the well-known ASME Boiler and Pressure Vessel Code. Thus it is of significance to undertake researches of transient sealing tests and analysis for nuclear vessel. Since 1960s great progress has been made in analytic computer program, which takes flange as a rigid ring. Actually, however, there are elastic or elastoplastic contacts on flange mating surface. Chen (1979) gave a mixed finite element method, using a condensing flexible matrix skill, to solve two-body contact problem. However, when concerning nuclear vessel, the situation will be more complicated because the bolt loading may change with internal pressure and temperature. So the problem becomes either an elastoplastic one with consisent loading change or one with thermal-elastic-contact coupling. Spaas (1977) considered elastoplastic stress distribution on the mating surface in coolant condition by using gap elements of MARC and Gu (1982) used adjustable gap to consider the effect of tightened bolts. In transient situation, the complicacy lies in the coupling between thermal and elastic effects in equation and boundary, and varying of loading caused by temperature lag at bolts. The latter effect is much stronger than the former. As a primary approximation, the transient temperature loading on determined boundaries should first be considered in sealing analysis.

On the basis of axisymmetric stress and thermal analysis of finite element method and on accepting Chen 's (1979) idea of mixed finite element method, we have developed a computer program for sealing analysis, named SMEC, which considers bolt loading changes and temperature effects.

2 FUNDAMENTAL EQUATIONS

On the basis of variation principle (Qian 1980) about thermal-elastic coupling, and on considering the system kinetic energy caused by rapid temperature changing, after the discretization through finite element method, two groups of 2D thermal-elastic equations can be obtained as follows:

$$(A) \qquad ([K]-[M]-[V])\{u\} = \{F\}+[G]\{T\}$$

(B) $$([C]+[W]+[S])\{T\} = \{Ta\}-[E]\{u\}$$

Here F is the equivalent loading vector, Ta, the temperature vector of medium. K, M are respectively the quasi-stiffness and quasi-mass matrices, and the other, the parameter or influence coefficient matrices.

Assuming small rate of temperature change with time, and thus neglecting the kinetic energy from the total energy of system, the coupling of thermal and elastic effects can be removed. In this condition, we simplify the above two groups of coupling equations into the following two groups of independent ones, considering the contribution of tensile and bending stiffness of bolt (K_F), taking O-ring as a bar having two stiffnesses (Ku,d) and using the spring-back performance test results of straight pipe:

(A1) $$\begin{bmatrix} K_I^* & 0 \\ 0 & K_{II} \end{bmatrix} \begin{Bmatrix} u_I \\ u_{II} \end{Bmatrix} = \{P\}+\{R\}+\{\Delta F\}+\{\Delta H\}$$

(A2) $$\{\Delta F\} = [K_F]\{\Delta u\}_b$$

(A3) $$\{\Delta H\} = [Ku,d]\{\Delta u\}_o$$

(A4) $$\{\Delta u\}_c = [Fb]\{R\}+\{u_F\}+\{e_o\}$$

(B1) $$[C]\{\partial T/\partial t\}+[\Lambda]\{T\} = \{F_T\}+\{\bar{Q}\}$$

(B2) $$\{\Delta T\} = [Fa]\{\bar{Q}\}+\{\Delta P_T\}$$ (for steady condition)

Here u and T are nodal displacement and transient temperature; R, the contact force on flange mating surface; F and H, the increments of bolt loading and O-ring force; and $\bar{Q}$, the heat flow through contact boundaries. These are unknown quantities. K is the stiffness matrix and I and II represent the two bodies. P is the given loading on boundaries, including equivalent nodal force of internal pressure, tightening force of bolt, O-ring reaction force and effective transient thermal loading. Subscripts b, o and c represent bolt, O-ring and contact node-pairs, respectively. Fb and Fa are flexibility matrices, u, the relative distance between contact node-pairs, e_o, the initial distance and u_F, the relative displacement at contact node-pairs caused by external loading. C and Λ are matrices of heat capacity and conduction, and P_T, the relative temperature differences at the contact node-pairs caused by the nodal heat loading, F_T.

In group A, u, R, F and H can be obtained by iterating (A1) through (A4). Then, in accordance with criteria of chamber and failure:

$$\Delta u1 \leq [\delta] \quad , \quad \Delta u2 \leq [\delta]$$

we can judge whether the cavity seeps or the seal fails. Here $[\delta]$ is the allowable spring-back, $\Delta u1$ and $\Delta u2$, the separations of flanges at inner and outer O-rings respectively. The contact reaction force calculation and the form of incremental equations used to consider the step by step loading addition are similar to those by Chen (1979). However, when performing step by step calculation, it is necessary to judge constantly whether the contac node-pairs should be rematched to adapt the over sliding deformation. In group B, temperature T can be solved when $\bar{Q}$ is known. $\bar{Q}$ can be determinded by contact- conduction condition. However, as the mating structure of nuclear pressure vessels is characteriz-

ed by two O-rings and 3 "islands", the small change of contact boundary in the seating cavity is not sensitive to heat conduction. Thus the thermal-elastic coupling on contact boundaries can also be removed. But due to the presence of bolt holes, heat conduction is delayed and consequent bolt loading discharges or addition may happen. So the above thermal analysis used in nuclear vessels should be corrected by analysis of 3D slice.

3 PROGRAM

On the basis of above fundamental equations, a computer program, named SMEC, for sealing analysis is developed. It can be easily used for comparing the leak-tightness characteristics of different designs. For instance, it is capable to show, on a computer terminal screen, the changes in the separations of flanges mating surfaces, the distribution of contact forces, the rotation of flange inside wall and the increment of bolt loadings with various structures and design parameters. The SMEC is verified by theoretical calculation (Dou 1987) and several tests (Qu 1987 and Sheng 1987). The program is proved to be of high precision and reliability.

As shown in Fig. 1, it could be noted that the increments of bolt loading with increasing pressure in the hydrotatic tests of vessels A, B and C present 3 types: monotonically increaing, monotonically decreasing and first decreasing and then increasing. The vessels are correspondingly classified, in the context of sealing characteristics, as type A, type B and type C. The calculated value and testing result are, respectively, as follows: For A, the bolt loading increases by 22% and 20%; for B, decreases by 10% and 6.7% ; for C, first decreases by 9% and 2% , then both linearly increases again. The calculated results by SMEC are always conservative in all cases. Fig. 2, 3 and 4 show, respectively the comparision between calculation and test of the separation and rotation of flange, thermal deformation and temperature field. These results can be considered satisfactory.

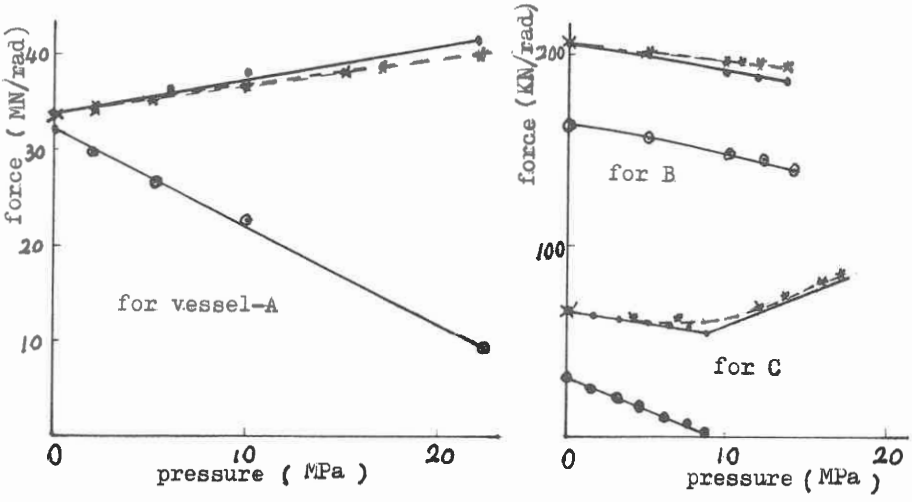

Figure 1. Bolt loading and contact force changed with pressure of vessel A, B and C.—•—: calculated value of b.l.;*--: measured value of b.l.; —o—: calculated value of c.f..

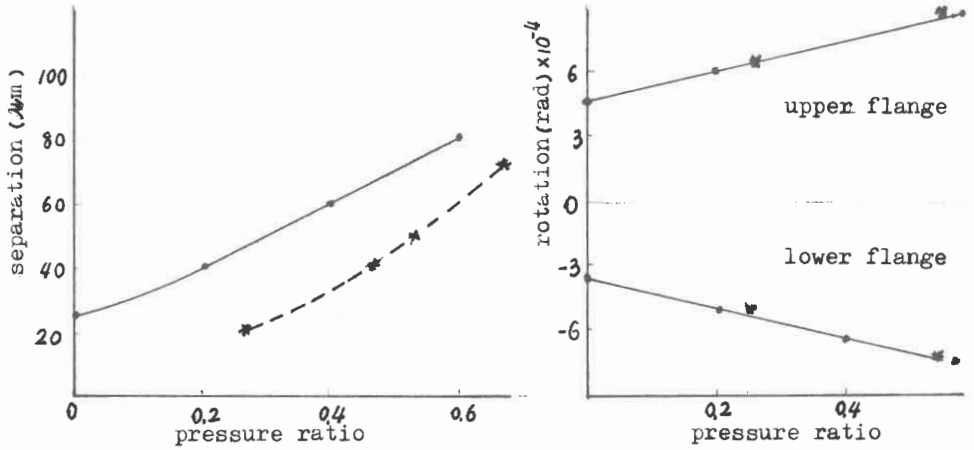

Figure 2. Separation of flanges and rotation of flange outside wall changed with pressure ratio. —•— : caculated value; *--: measured value.

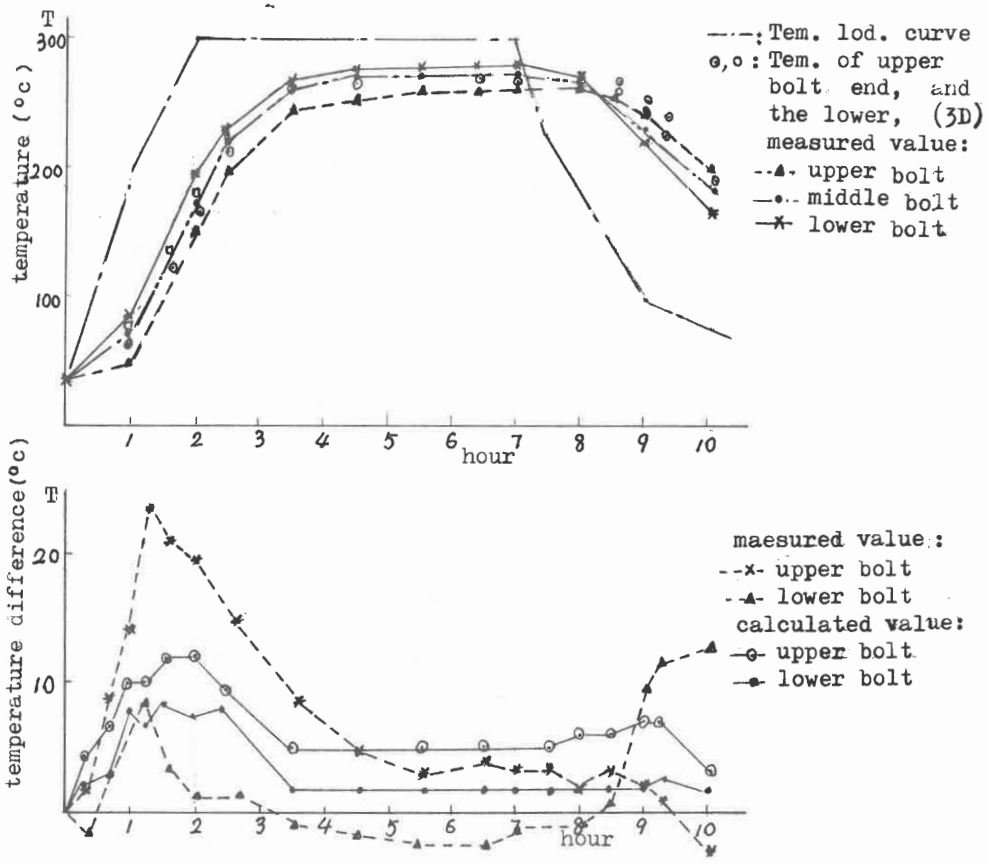

Figure 3. Temperature changing of bolts and temperature difference between bolt holes and bolts during the time of heat-up and cool-down.

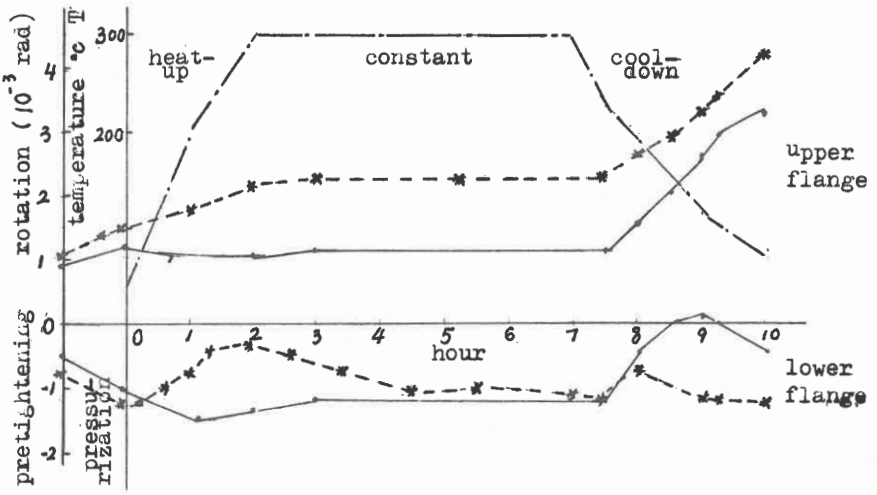

Figure 4. Flange rotation-time curve of vessel B in the test. On the last stage of cool-down, the rotation of upper flange increases rapidly while the bolt loading decreases by 11% due to the effect of bolt-lag. In this case, the leak will probably be happened if the O-ring is made of stainless steel.

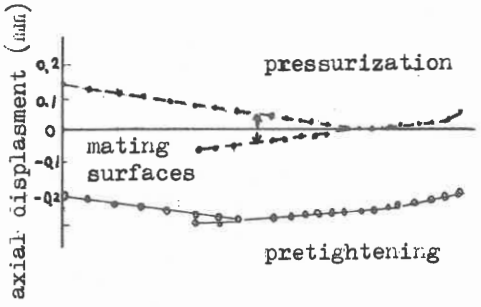

Figure 5. Deformation pattern for vessel A on mating surfaces.

Table 1. Compression of mating surfaces for vessel A (μm).

Condition	Inside	
	Upper	Lower
Pretightening	3.3	1.5
Pressurization	0	0
	Outside	
	Upper	Lower
Pretightening	35.1	22.8
Pressurization	25.5	7.1

4 ANALYSIS AND DISCUSSION

SMEC program was used to analyze the sealing behaviours for several pressure vessels. The behaviours are evaluated by direct criteria, which include the distribution of reaction force, the compression and separation of flange mating surfaces, and, in case these are not readily measurable, by indirect criteria, which include the increment of bolt loading and the rotation angle of outside flange wall.

4.1 Deformation pattern

Analysis results show that the flange mating surfaces can be divided into three areas, i.e., elastic contact area, wedge-open area and small plas-

tic area. The compression of flange mating surfaces is a measure of sealing capability. The middle and outer islands may be considered as a distributed spring, it will be compressed when pretighteding the bolts, and the compression will be released from inside to outside after exerting pressure.

4.2 A new concept of pressure vessel

As shown in Fig. 1, a new concept of classifying vessels into three types (type A, B and C) according to the changing of bolt loading, is suggested. This is important for vessel design, because distinguishing the types through analysis can form a basis for determining pretightening factor of bolt, so that the over loading and the relaxation of bolts, which may respectively decrease the fatigue life of bolts and cause leakage, can be avoided.

4.3 Sealing mechanism and sealing condition

The essence of sealing analysis lies in the deformation analysis for flange-bolt-shell system of vessel under various loading and boundary conditions, neglecting the technology factor on the gasket surface. The sealing of vessel is assured by the reaction force and spring-back of O-ring with certain flattening. The spring-back compensates the separation of flange in axial direction, while the O-ring reaction force (special sealing pressure) provides resistance to radial seepage caused by internal pressure. The O-ring slot gives certain flattening for O-ring, thus the flange mating surface becomes a distributed spring which stores energy during pretightening.

Excessive stiffness difference between the upper and lower flanges will result in relative movement between the two in horizontal direction. This may cause transient leakage and scratch the plating layer of the O-ring. The secure contact between O-ring and the mating surfaces (gasket face) and the packing effect of the plating layer are necessary conditions to prevent micro-seepage. The essence of two O-ring sealing system lies in that at any time only one O-ring is actually on duty. The outer O-ring, being near the bolts, generally can assure leak tightness, therefore, it seems certain that the main factor causing leakage through the outer ring is the temperature lag of the bolt at the last stage of cooldown.

From discussions above we present 4 sealing conditions as follows:

1. Axial condition: In O-ring portion, the separation of flanges caused by mechanical loading should be less than spring-back.
2. Radial condition: Relative radial motion between the upper and lower flanges should be prevented by the friction on mating surfaces.
3. Temperature difference condition: Axial and radial thermal deformation caused by temperature gradient and temperature lag in bolts should be given by thermal analysis or test, and then the above two conditions be considered.
4. Circumferential and seepage condition: The separation between the flanges should be evenly distributed in circumferential direction and less than the allowable spring-back of O-ring. The silver layer on O-ring should be capable of compensating the microunevenness at gasket surfaces.

These are our understandings of sealing problem of nuclear vessel, and, also, the basis of performing the tests and analysis.

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