Brief Analysis Calculation Method of Closure Head Multi-holes Region Thickness for Reactor Pressure Vessel

Lihong Zhai\textsuperscript{1, a}, Guangyao Lu\textsuperscript{1, b}, Yang Jiang\textsuperscript{2}, Jing Wang\textsuperscript{3, *}

\textsuperscript{1}China Nuclear Power Technology Research Institute Co, Ltd, Shenzhen, Guangdong Prov, China
\textsuperscript{2}China Nuclear Power Technology Research Institute Co, Ltd, Shenzhen, Guangdong Prov, China
\textsuperscript{3}Environmental Protection Department Nuclear and Radiation Safety Center, Beijing, China

*Corresponding author e-mail: kagaiboshi@sina.com, azhailihong@cgnpc.com.cn, luguangyao@cgnpc.com.cn

Abstract. The article introduced the base wall thickness calculation method of closure head region with more openings for reactor pressure vessel. Analysis was also conducted to explain the source of the method. So the method can provide the basic data for Finite Element detail analysis calculation, and it is verified by result of analysis calculation.

1. Introduction

The reactor pressure vessel is an enclosed containment vessel that anchors and accommodates the reactor core and bear the high temperature and pressure, also known as the RPV. The reactor pressure vessel works as the pressure boundary to support and accommodate reactor cores. The reactor pressure vessel connects with the dome structure and reactor coolant pipeline besides accommodating the reactor core, reactor core support structure, control rod and other components directly connecting with reactor core, and contacts the reactor vessel support fixed on the concrete structure located inside the reactor containment [1]. It is only non-replaceable unit in the primary loop components of Reactor Island, therefore it is extremely critical for the design of the component.

The closure head of reactor pressure vessel is one of the nuclear class 1 component, which requires the design requires the analytical method for design, but for the basic calculation method of closure head multi-holes region thickness for reactor pressure vessel, there is no specific regulation in the NB subsection of ASME Code. This paper introduced the basic wall thickness calculation method of closure head region with more openings for reactor pressure vessel. Analysis was also conducted to explain the source of the method in order to provide the basic structure data for Finite Element Analysis.
2. Basic data

2.1. Description of geometrical shape

The dome head is composed of a semi-spherical upper head and flange, the inner surface is overlaid, and the head is provided with multiple control rod drive mechanism (CRDM) penetration assemblies, and accommodating several in-core instrumentation thimbles (ICI) and a discharge pipe penetration assemblies.

The hemispherical head is made from an integral forging with low alloy carbon steel and the whole coolant wetted surfaces are deposit welded with stainless steel welding layer. As for material, it may find out the design stress strength $S_m$ at temperature in table 2A of chapter D, Section II, ASME Code.

2.2. Loading Condition

Dimension calculation requires the design pressure $P$ and the design temperature $T$.

3. Determination of Dome Head Thickness and Method Analysis

The design calculation size is determined according to NB-3122, ASME Code.

It is noted that during the calculation of primary stress, the deposit welding layer will not bear the structure strength. Only when welding layer thickness exceeds 10% of base metal, it will be considered in the strength of welding layer [2].

3.1. Thickness Calculation of Dome Head without Holes and Origin of Equation

Calculate as per NB-3324.2

$$
t = \begin{cases} 
\frac{PR_o}{2S_n} & \text{or} \\
\frac{PR}{2S_n - P} 
\end{cases} \quad (1)
$$

Where: $P$-Design pressure;
$T$-Design temperature;
$R$-Inside radius of dome head (internal surface of base metal);
$R_o$-Outside radius of dome head (external surface of base metal);
$S_m$-Design stress strength.

The above equation is the equation derived from the middle diameter formula of the rotational shell without moment theory based on the third strength theory, i.e.

$$
t = \frac{PR_o}{2S_n} \quad (2)
$$

In the design of nuclear class 1 component, it generally follows the principle of the conservation. Substitute the average radius $R_m$ as the outside radius $R_o$, then the expression of outside diameter in the equation (1) is obtained, then substitute $R_o=R+t$ into the expression of outside radius, then the expression of inside radius of the equation (1) is obtained.

Generally, when the ration between the wall thickness of metal shell and max. sectional area of shell is less than or equal to 0.05, if there is no abrupt change of wall thickness, material, curvature radius and loading conditions of shell, the internal moment may be ignored during the calculation and it will cause much affect to the calculation result. Such ignorance theory of internal moment and transverse shear is called as the moment free theory, also known as the membrane theory of shells. In the pressure vessel field, it usually call the shell $K>1.2$ as thick wall shell, and the shell $K\leq 1.2$ as thin
wall shell, where $K = D_o/D_i$, $D_o$ and $D_i$ are the outside diameter and inside diameter of shell respectively. In the engineering practice aspect, it generally names the shell which ratio between the wall thickness and the diameter of max. Section area of shell less than or equal to 0.05 as the thin wall shell [3].

3.2. Calculation Method and Analysis of Required Thickness of Multi-Holes Region of Head

3.2.1. Ligament Efficiency Method. Calculate the required thickness of multi-holes region, including the CRDM and ICI penetration assemblies in accordance with the following equation:

$$t_{\text{perf}} = \frac{t_{\text{max}}}{\eta}$$  \hspace{1cm} (3)

Where: $t_{\text{max}}$ is the max. Value in sec. 2.1.

$\eta$ - Ligament efficiency

$$\eta = \frac{h}{P} = \left\{ \begin{array}{ll} \frac{h_1}{P_1} = \eta_1 (\text{See note 1}) \\ \frac{h_2}{P_2} = \eta_2 (\text{See note 2}) \end{array} \right\}$$  \hspace{1cm} (4)

Find the closed hole as shown in Fig. 1.

Fig 1. Schematic Diagram of Considered Hole Arrangement

$h$ – Nominal ligament width at min. sectional area

P-Nominal distance between center lines of two holes (center distance)

$$h = \left\{ \begin{array}{ll} P_1 - (D_i/2 + D_i/2) = h_1 (\text{See note 1}) \\ P_2 - D_i = h_2 (\text{See note 2}) \end{array} \right\}$$  \hspace{1cm} (5)

$$P = \left\{ \begin{array}{ll} P_1 (\text{See note 1}) \\ P_2 (\text{See note 2}) \end{array} \right\}$$

$$t_{\text{perf}} = \frac{t_{\text{max}}}{\eta_1} \quad (\text{See note 1})$$
Actual thickness $t_{\text{actual}} \geq$ the above calculated max. Thickness of $t_{\text{perf}}$.

Note: 1. Consider 1 hole D2 and 1 hole D1, $D1 > D2$; 2. Consider 2 holes D2.

The above mentioned ligament efficiency method is to calculate the strength reduction of the vessel caused by the opening holes, also known as the ligament efficiency, which is widely applied in the boiler and heat exchanger industries [4]. The ligament efficiency refers to the coefficient of the strength reduction of the component when it has a row of opening holes on the vessel, plate and other pressure containing parts.

There is no description of calculation method of ligament efficiency for multi-holes in the NB subsection of ASME Code, but in the NC-3329 of NC subsection of ASME Code, there is the description of calculation method of ligament efficiency for multi-holes, which could be referenced to determine the basic thickness of dome head with multi-holes. It seems that this method is simple and useful.

3.2.2. Calculation Method of Opening Reinforcement. Evaluate the correct thickness of reduced multi-holes region considering the need for opening reinforcement. For Fig. 1:

**Reinforcement area for section A-A**

$$A_{\text{req1}} = t_{\text{max}} \times D_2$$

**Reinforcement area for section B-B**

$$A_{\text{req2}} = t_{\text{max}} \times D_1$$

**Reinforcement range (from center line):**

Reinforcement range along the wall of head (ASME Code NB-3334.1)

$$L_4 = \max \left\{ \frac{D_1}{2} + t_{\text{wall}} + t_{\text{wall}}, \frac{D_2}{2} - t_{\text{wall}} \right\}$$

(6)

$$L_{234} = \max \left( \frac{D_1}{2} + 0.5 \sqrt{\frac{D_1^2}{4} + \frac{D_2^2}{4} + \frac{2}{3} t_{\text{wall}}^2} \right)$$

(7)

$R_0$ - Average radius of head
$t_{\text{n}}$ - Nominal thickness of head

Reinforcement scope in section A-A of Fig.1 is $0.5 \times (P_2 - D_2)$
Reinforcement scope in section B-B is $\delta \times (P_1 - D_1)/2 - D_2/2)$

The area between two holes may be considered as the area between the respective diameters. Therefore there is large holes as follows:

$$\frac{D_1}{D_1 + D_2} = \delta$$

(8)

Available area:
Section A-A (See Fig. 1)
Section B-B (See Fig.1)

\[ A_{\text{req}}, L - A = (t_{\text{actual}} - t_{\text{min}}) \times (P_2 - D_2) > A_{\text{req}} \]

For those areas which primary local membrane stress of local stress area of vessel does not exceed 1.1Sm, the reinforcement is not necessary. But, in fact, all the primary local membrane stress of those areas with multi-holes will exceed the limit, therefore all of these are subject to the opening reinforcement calculation.

If the area of the above calculated effective reinforcement range is more than actual available range, then it may calculate in accordance with the requirement of NC-3335.2 of ASME Code [5], but considering the loading combination of various operation conditions of the equipment, the actual available area may be determined in a conservative way, i.e. it may calculate the actual available equivalent diameter range or take the diameter range other than the overlapped area, and the nozzle is not involved in the reinforcement, see Fig.2.

Fig 2. Limits of reinforcement for multi-openings

If opening holes are located close to the edge of head, the drop and diameter is quite large, then it should consider to design the connection between flange and head in form of reinforced cone transition section (shown as Fig.3) to increase the flange rigidity and head strength and decrease the boundary stress at connection area of flange and head.

Fig 3. Connection structure of flange and head
3.2.3. Verification min. Arc Length between Multi-holes. Generally, the distance between holes shall comply with the rules of NB-3338 of ASME Code, i.e. the min. arc length distance between adjacent holes on the head (measured along the inner surface) shall not be less than 3 times of the sum of radius of such holes [2].

Consider the adverse conditions (i.e. the condition that it is even less than the required min. distance):

\[ L_{\text{min,adj}} = P_2 \geq 3 \times D_2 \]

\[ L_{\text{min,B-A}} \approx P_1 / \cos a > 3 \times (D_1 / 2 + D_2 / 2) \]

It will satisfy the above requirements.

Fig 4. Sketch of space between opening holes

The above requirements are the stress exponent of opening holes that satisfies the subsequent fatigue estimation, which is determined through a large number of experimental methods and numerical analysis methods. It is simple and easy to use, especially suitable for engineering design.

For the individual opening holes do not meet the above requirements, it will be acceptable if only the reinforcement area meets the requirements. If the equivalent area reinforcement calculation (this method is too conservative), it still can not meet the requirements, then the detailed analysis and calculation will be conducted.

4. Result Verification of FEA Calculation
The calculation methods are the preliminary estimation to provide the basis of structure data for further analysis and calculation. The specific thickness and stress requirements will require further verification.

The result of analysis calculation is shown as following Fig.5 and 6, where all the results of primary stress Pm, Pt, Pl+Pb and tri-axial stress in the design condition after installing the nozzle have satisfied the evaluation requirements given in NB subsection of ASME Code, which verified the correctness of preliminary thickness calculation.
Fig 5. Load boundary condition

Fig 6. Stress distribution cloud map
5. Conclusion
There are no specific requirements for the basic calculation method of multi-holes region thickness of dome head of reactor pressure vessel in the NB subsection of ASME Code.

This paper focused on the multi-holes condition of dome head of reactor pressure vessel, introduced the basic calculation method of multi-holes region thickness of dome head of reactor pressure vessel, stated two kinds of calculation methods by means of ligament efficiency and opening reinforcement method as well as the arc length between multi-holes to verify the thickness of multi-holes region of the head. The paper made the brief analysis and provided the recommendation for engineering application and provide the basic structure parameters for subsequent FEA detailed calculation. Through the FEA and calculation, it has satisfied the requirements of the Code, and it also provides a reference calculation method for the strength calculation and structure size determination of the multi-opening holes of dome heads for other similar components.

Bibliography
[1] An Advanced Passive Plant AP1000 /by Lin Chengge.—Beijing: Atomic Energy Press, 2008.8
[2] ASME Code Section III Division 1-Subdection NB Class 1 Components Rules for Construction of Nuclear Facility Components, 2007
[3] Process Equipment Engineering/by Zheng Jinyang etc, Beijing: Chemical Industry Press, 2001
[4] Suggestions on expanding the ligament efficiency restrictive conditions of vessels/ by Liu Feng, Zhang Ming, Liu Wentie and Li Zhiguang, China Special Equipment Safety, Vol.9, 2009
[5] ASME Code Section III Division 1-Subdection NC Class 2 Components Rules for Construction of Nuclear Facility Components, 2007