Chapter 2
Mechanical Basics

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Abstract In this section, some basic information which is helpful to understand the following chapters, for example, the material mechanics, introduces stress and deformation in typical components, as well as the judgment method; and the contact mechanics explains the stress concentration and relieving solutions; some subjects may not belong to the mechanics type, but they can provide explanation about the loads onto the tokamak structures, thus these courses are also included, for example, fluid mechanics describes the coolant pressure inside the blanket or vacuum vessel, and electromagnetism shows the source of the Lorentz force. Due to space limitations, this section does not bring in much mathematic deduction, but gives description of basic concepts and representative cases for reference.

2.1 Mechanics in Tokamak

2.1.1 Material Mechanics

2.1.1.1 Introduction

The material mechanics is widely used in the tokamak design, which calculates the structure strength, rigidity, and stability and extracts stress, strain, and deformation. Generally a structure should have enough strength to withstand all kinds of loads; and with some special requirement of geometry, such as clash problem inside the narrow tokamak machine, high rigidity is required; for certain structures that may have buckling problem, stability should be checked.

The material mechanics focus on the internal force, stress, and deformation, its formulas solve these parameters to judge a mechanical design; this is different from rigid body mechanics, which does not consider the deformation of the concerned object.

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To simplify the calculation, there are three basic assumptions:

- Continuity assumption: it assumes that the material fills the whole volume, which means there is no gap; however, in reality there must be some gaps between the material particles, and these gaps will change with the external loads, which makes the situation complicated, but if the gap size is negligible than the object, the material could be considered continuous.
- Homogeneity assumption: it assumes the material properties are uniform everywhere, in fact, due to the complex particle structure inside the object and the particle property difference, the material property cannot be uniform everywhere. However, because the particle size is much smaller than the object and their positions are randomly arranged, the global property could be considered as an average value inside the volume.
- Isotropy assumption: it assumes the material properties are uniform in every direction. For example, metal consists of small grains, and each grain has its own oriented properties, but the grains cross each other, then the macroscopical object property could be considered uniform in any direction, like glass, milling steel plate, and plastic. However, some materials are not isotropy, like wood and composite materials.

If the solid deformation under external load is limited in a range, when the load is removed, the object could recover its original shape and size, and then this deformation is considered elastic and the value of this range represents the material's elasticity. While the load exceeds the range, the object cannot restore and the deformation is plastic. In most engineering applications, only elastic deformation is allowed, and the material mechanics focuses on the elastic cases.

There are three basic types of objects which are studied in the solid mechanics:

- Bar: this type of object can be described by an axis and the cross section along the axis, and the section size is much smaller than the axis length.
- Shell: this type of object has a large surface and much smaller thickness compared to the surface size. The area which is located in the middle of the thickness is called mid-surface, if it is flat, the object is considered as a plate, and if it is curve, the object is a shell.
- Block: this type of object is very common; it has similar dimensions in all three directions.

2.1.1.2 Basic Formula

The material mechanics mainly studies the bar problems; there are four basic deformations of the bar:

- Axial tension or compression: a tensile or compressive force is applied on the axis and makes axial deformation.

- Shear: two opposite transverse forces are applied on the bar at close positions with the same magnitude, then the bar will have transverse section deformation, and this phenomenon is called shear.
- Torsion: an axial moment is applied to the cross section, then the bar suffers a rotation along the axis, and this deformation is torsion.
- Bending: if a sideways force on the axis, or a moment in the plane which includes the axis, is applied on the bar, then the bar bends and this is called bending.

A complex deformation is defined as two or more basic deformation combinations.

Under the axial tension or compression, the stress formula is

$$\sigma = \frac{F_N}{A} \tag{2.1}$$

where σ is the axial stress Pa; F_N the axial force N; and A the cross section area m^2. Generally, tensile stress is marked as positive stress and compressive stress is negative.

The axial deformation is given in the strain formula

$$\in = \frac{F_N}{E \cdot A} \tag{2.2}$$

where ε is the axial strain, dimensionless; and E the elasticity modules Pa.

Under the shear force, the shear stress is calculated as

$$\tau = \frac{F_T}{A} \tag{2.3}$$

where τ is the shear stress on the cross section Pa; andF_T the shear force N.

Under the torsion, the maximum shear stress formula is

$$\tau_{max} = \frac{M_x \cdot r}{I_P} \tag{2.4}$$

where τ_{max} is the maximum shear stress Pa; M_x the torque applied on the bar section $N \cdot m$; r the largest distance from the axis to the edge of the cross section m; and I_P the polar inertia moment of the cross section m^4.

The deformation is described with a unit rotation angle

$$\theta = \frac{M_x}{G \cdot I_P} \tag{2.5}$$

where θ is the unit rotation angle rad/m; and G the material shear modules Pa.

Under the bending loads, the maximum bending stress formula is

$$\sigma_{max} = \frac{M \cdot y}{I} \tag{2.6}$$

where $\sigma_{\max}$ is the maximum bending stress Pa; M the bending moment N · m; y the farthest distance from the neutral surface to the edge m; and I the cross section inertia moment to the neutral axis m^4.

The bending deformation is described with two parameters, the rotation angle and bending deflection, their formulas are:

$$\theta_{\max} = \frac{FL^2}{2EI} \tag{2.7}$$

$$\omega_{\max} = \frac{FL^3}{3EI} \tag{2.8}$$

where $\theta_{\max}$ is the maximum rotation angle rad; $\omega_{\max}$ the maximum deflection m; F the sideways force on the axis N; and L the length of the bar m.

2.1.1.3 Stress and Strength Theory

The state of stress at a point inside an object is always described in a block element which is located in the point and has infinitely small size, three planes that are perpendicular to each other and can be defined to extract the three principal stresses. If there are two zero principal stresses, it is called the uniaxial stress state; if only one is zero, it is biaxial stress state; and if none is zero, it is three-dimensional stress state.

For a surface in biaxial stress state, the stress in any direction can be calculated using the formula

$$\sigma_\alpha = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\alpha - \tau_x \sin 2\alpha \tag{2.9}$$

$$\tau_\alpha = \frac{\sigma_x - \sigma_y}{2}\sin 2\alpha + \tau_y \cos 2\alpha \tag{2.10}$$

where α is the angle between the surface normal direction and the x-axis.

For an element in three-dimensional stress state, the principal stress and principle strain have the following relationship, called generalized Hook's law:

$$\varepsilon_1 = \frac{1}{E}[\sigma_1 - \gamma(\sigma_2 + \sigma_3)] \tag{2.11}$$

$$\varepsilon_2 = \frac{1}{E}[\sigma_2 - \gamma(\sigma_3 + \sigma_1)] \tag{2.12}$$

$$\varepsilon_3 = \frac{1}{E}[\sigma_3 - \gamma(\sigma_1 + \sigma_2)] \tag{2.13}$$

Generally speaking, there are four classic strength theories.

- Maximum tensile stress theory, which is called the First strength theory, defines the stress limit as the maximum tensile stress, which means the condition of failure is $\sigma_L = \sigma_b$; this theory is suitable for crispy materials.
- Maximum tensile strain theory, which is the Second strength theory, defines the condition of failure as the maximum tensile strain gets the break limit, $\varepsilon_L = \varepsilon_b$; this theory considers the other two principal stresses' impact, and can be described as $\sigma_1 - \gamma(\sigma_2 + \sigma_3) = \sigma_b$. This theory is suitable for concrete structures, but not fit for other materials.
- Maximum shear stress theory, as the Third strength theory, defines the failure condition as the maximum shear stress gets the yield limit $\tau_{\max} = \tau_s$; this formula can be described as $\sigma_1 - \sigma_3 = \sigma_s$. The left of the formula is also called Tresca stress. This theory is suitable for plastic materials in most applications, and is used widely due to its simplicity and higher margin than other theories. However, the second principal stress is not included.
- The Fourth strength theory is the shape change energy density theory, which defines the break limit as the maximum shape change energy density getting the yield limit under axial tension, as $\nu_d = \nu_{du}$; it can also be defined with principal stresses as $\sqrt{\frac{1}{2}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]} = \sigma_s$; this stress is also called von mises stress; it includes all three principal stresses and is more accurate than the tresca stress, so the application range is wide.

These theories provide a method to judge the rod in complicated stress state. But it is difficult to choose a proper theory in the engineering practice. Materials, load category, and working temperature all have impact on the choice. Generally speaking, in room temperature and static load state, a brittle material is easy to break, thus the maximum tensile stress or strain theories are chosen; while for plastic materials, the yield failure is common, and the maximum shear stress and shape change energy density theories are proper.

However, a material can have different failures in different stress states. For low carbon steel, in uniaxial tensile state, the yield failure occurs, and the third and fourth theories are chosen; but in three-dimensional tensile state, brittle failure appears and the first and second theories fit better. For both plastic and brittle materials in three-dimensional compression state, yield failure dominates, and the third and fourth theories are proposed. Therefore, there are many issues to be noticed in engineering practice.

2.1.2 Elasticity Mechanics

2.1.2.1 Introduction

Elasticity could be considered as an extension of the material mechanics, which has less assumption and could be more realistic. In the engineering design, to ensure safety and reliability, the deformation is constrained in the elastic region and could recover to the initial status after unload, and the elasticity is widely used. The internal force, strength, rigidity, and stability are also targets of elasticity. It shares the basic assumptions with the material mechanics, including continuity, homogeneity, isotropy, elastic, and small deformation and zero initial stress. The difference mainly exists in the detailed assumption, like the plane deformation and stress distribution assumptions, which are called additional assumptions,

2.1.2.2 Basic Formula

Differential equations of equilibrium are also called Navier equations.

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + F_x = 0 \tag{2.14}$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + F_y = 0 \tag{2.15}$$

$$\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z} + F_z = 0 \tag{2.16}$$

Geometry equations are also called Cauchy equations.

$$\varepsilon_x = \frac{\partial u}{\partial x}, \gamma_{yz} = \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \tag{2.17}$$

$$\varepsilon_y = \frac{\partial v}{\partial y}, \gamma_{zx} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x} \tag{2.18}$$

$$\varepsilon_z = \frac{\partial w}{\partial z}, \gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \tag{2.19}$$

Generalized Hook's law is the same as the material mechanics, which can also be described by strains.

$$\sigma_x = \frac{E}{1+v}\left(\frac{v}{1-2v}\theta + \varepsilon_x\right), \tau_{yz} = \frac{E}{2(1+v)}\gamma_{yz} \tag{2.20}$$

$$\sigma_y = \frac{E}{1+v}\left(\frac{v}{1-2v}\theta + \varepsilon_y\right), \tau_{zx} = \frac{E}{2(1+v)}\gamma_{zx} \tag{2.21}$$

$$\sigma_z = \frac{E}{1+v}\left(\frac{v}{1-2v}\theta + \varepsilon_z\right), \tau_{xy} = \frac{E}{2(1+v)}\gamma_{xy} \tag{2.22}$$

In the following sections, some typical cases are summarized:

For a cantilever beam which has a force P on the free end in perpendicular direction, the beam weight can be ignored, the length of the beam is L, the sectional height and width is h and 1 respectively, the coordinate system is located in the fixed end of the beam, and the x-axis points along the beam to the free end, while the y-axis points to the same direction of the force.

The stress function could be expressed as

$$\varphi = \frac{A}{6}(l-x)y^3 + y\left(Bx^3 + Cx^2 + Dx + E\right) + Fx^3 + Gx^2 + Hx + K \tag{2.23}$$

The plane stress components are calculated as below:

$$\sigma_x = \frac{\partial^2\varphi}{\partial y^2} = A(l-x)y \tag{2.24}$$

$$\sigma_y = \frac{\partial^2\varphi}{\partial x^2} = 6(By+F)x + 2(Cy+G) \tag{2.25}$$

$$\tau_{xy} = -\frac{\partial^2\varphi}{\partial x\partial y} = \frac{A}{2}y^2 - 3Bx^2 - 2Cx - D \tag{2.26}$$

The boundary conditions can be defined as:

$$\left(\sigma_y\right)_{y=\pm\frac{h}{2}} = 0 \tag{2.27}$$

$$\left(\tau_{yx}\right)_{y=\pm\frac{h}{2}} = 0 \tag{2.28}$$

and the stress solution is:

$$\sigma_x = -\frac{P}{J}(l-x)y, \sigma_y = 0 \tag{2.29}$$

$$\tau_{xy} = \frac{P}{2J}\left(\frac{h^2}{4} - y^2\right) \tag{2.30}$$

where $J = \frac{h^3}{12}$ is the inertia moment of the beam section.

Displacement solution is

$$u = \frac{P}{EJ}\left(-lxy + \frac{1}{2}x^2y - \frac{2+v}{6}y^3\right) + \frac{1+v}{4EJ}Ph^2y \tag{2.31}$$

$$v = \frac{P}{2EJ}\left(vly^2 - vxy^2 + lx^2 - \frac{1}{3}x^3\right) \tag{2.32}$$

To a simply supported beam which takes distributed load of q, the width of the beam is also one unit, and the weight of the beam is ignored; the stress function is described as:

$$\varphi = \frac{x^2}{2}\left(Ay^3 + By^2 + Cy + D\right) + x\left(Ey^3 + Fy^2 + Gy\right) - \frac{A}{10}y^5 - \frac{B}{6}y^4 + Hy^3 + Ky^2 \tag{2.33}$$

Stress components are described as:

$$\sigma_x = \frac{\partial^2 \varphi}{\partial y^2} = \frac{x^2}{2}(6Ay + 2B) + x(6Ey + 2F) - 2Ay^3 - 2By^2 + 6Hy + 2K \tag{2.34}$$

$$\sigma_y = \frac{\partial^2 \varphi}{\partial x^2} = Ay^3 + By^2 + Cy + D \tag{2.35}$$

$$\tau_{xy} = -\frac{\partial^2 \varphi}{\partial x \partial y} = -x\left(3Ay^2 + 2By + C\right) - \left(3Ey^2 + 2Fy + G\right) \tag{2.36}$$

The solution of these equations could make use of the symmetric phenomenon, which is:

$$\sigma_x(x, y) = \sigma_x(-x, y) \tag{2.37}$$

$$\sigma_y(x, y) = \sigma_y(-x, y) \tag{2.38}$$

$$\tau_{xy}(x, y) = -\tau_{xy}(-x, y) \tag{2.39}$$

Other boundary conditions include:

$$\left(\sigma_y\right)_{y=-\frac{h}{2}} = -q,\ \left(\tau_{yx}\right)_{y=-\frac{h}{2}} = 0 \tag{2.40}$$

$$\left(\sigma_y\right)_{y=\frac{h}{2}} = 0,\ \left(\tau_{yx}\right)_{y=\frac{h}{2}} = 0 \tag{2.41}$$

and the final stress solution is

$$\sigma_x = \frac{M}{J}y + \frac{q}{h}y\left(\frac{4}{h^2}y^2 - \frac{3}{5}\right) \tag{2.42}$$

$$\sigma_y = -\frac{q}{2}\left(1 + \frac{y}{h}\right)\left(1 - \frac{2y}{h}\right)^2 \tag{2.43}$$

$$\tau_{xy} = \frac{QS}{bJ} \tag{2.44}$$

where $J = \frac{h^3}{12}$, $S = \frac{h^2}{8} - \frac{y^2}{2}$, $b = 1$, $M = \frac{q}{2}\left(l^2 - x^2\right)$, $Q = -qx$.

To a sphenoid which suffers the gravity ρg and sideways pressure like water pressure $\gamma g y$, where ρ and γ is the density of the sphenoid and water, respectively.

The stress function can be described as

$$\varphi = ax^3 + bx^2y + cxy^2 + dy^3 \tag{2.45}$$

$$\nabla^4\varphi = 0 \tag{2.46}$$

The stress can be defined as

$$\sigma_x = 2cx + 6dy \tag{2.47}$$

$$\sigma_y = 6ax + 2by - \rho gy \tag{2.48}$$

$$\tau_{xy} = -2bx - 2cy \tag{2.49}$$

The boundary conditions are

$$(\sigma_x)_{x=0} = -\gamma gy \tag{2.50}$$

$$\left(\tau_{yx}\right)_{x=0} = 0 \tag{2.51}$$

$$\mathrm{l} = \cos\alpha \tag{2.52}$$

$$\mathrm{m} = \cos\left(\alpha + \frac{\pi}{2}\right) = -\sin\alpha \tag{2.53}$$

$$\overline{T_x} - \overline{T_y} = 0 \tag{2.54}$$

The stress solution is

$$\sigma_x = -\gamma gy \tag{2.55}$$

$$\sigma_y = \left(\rho g\cot\alpha - 2\gamma g\cot^3\alpha\right)x + \left(\gamma g\cot^2\alpha - \rho g\right)y \tag{2.56}$$

$$\tau_{xy} = -\gamma gx\cot^2\alpha \tag{2.57}$$

For a thick-walled cylinder which takes both inner and outer pressure loads, the stress can be expressed as:

$$\sigma_r = \frac{A}{r^2} + 2C \tag{2.58}$$

$$\sigma_\theta = -\frac{A}{r^2} + 2C \tag{2.59}$$

$$\tau_{r\theta} = 0 \tag{2.60}$$

The boundary conditions are:

$$(\sigma_r)_{r=a} = -q_a, (\tau_{r\theta})_{r=a} = 0 \tag{2.61}$$

$$(\sigma_r)_{r=b} = -q_b, (\tau_{r\theta})_{r=b} = 0 \tag{2.62}$$

where a and b are the inner and outer radii of the cylinder, q_a and q_b are the inner and outer pressures, respectively.

The stress in the cylinder wall can be solved as

$$\sigma_r = \frac{-\frac{b^2}{r^2} - 1}{\frac{b^2}{a^2} - 1} q_a - \frac{1 - \frac{a^2}{r^2}}{1 - \frac{a^2}{b^2}} q_b \tag{2.63}$$

$$\sigma_\theta = \frac{\frac{b^2}{r^2} + 1}{\frac{b^2}{a^2} - 1} q_a - \frac{1 + \frac{a^2}{r^2}}{1 - \frac{a^2}{b^2}} q_b \tag{2.64}$$

$$\tau_{r\theta} = 0 \tag{2.65}$$

If this cylinder is constrained at the outer perimeter, and only inner pressure q has impact, then the same stress equations could be solved with different boundary conditions

$$\sigma_r = -\frac{qa^2(1-2v)b^2 + r^2}{r^2(1-2v)b^2 + a^2} \tag{2.66}$$

$$\sigma_\theta = \frac{qa^2(1-2v)b^2 - r^2}{r^2(1-2v)b^2 + a^2} \tag{2.67}$$

$$\tau_{r\theta} = 0 \tag{2.68}$$

and the deformation is

$$u_r = \frac{(1+v)(1-2v)a^2 q}{E[(1-2v)b^2 + a^2]} \left(\frac{b^2}{r^2} - r \right) \tag{2.69}$$

$$u_\theta = 0 \tag{2.70}$$

2.1.2.3 Stress Concentration

Introduction

Stress concentration refers to the stress in the local area that has significantly increased as a result of external factors or factors geometry, dimensions mutation. For construction element which is made of brittle material, the phenomenon is always maintained at the maximum local stress before reaching the ultimate strength. Therefore, you must consider the impact of stress concentration in the design of brittle material components. Certainly, some method can be taken to avoid stress concentration, such as eliminate sharp corners, improve the component shape, add local strengthening hole and increase the degree of finish of the material surface, etc. On the other hand, measures, for instance shot peening, roll pressure, oxidation, and other processing on the surface of the material can be taken to enhance the fatigue strength of the surface of the material.

Some typical cases

- Two-ball contact problem

Two-ball contact problem is very important in Mechanical Engineering. It is necessary to consider its deformation under load, if the stress is to be confirmed. At first, some basic principles as follows are given for derivation of the formal, since the problem is complex.

- Geometric distortion conditions
  According to the geometric principle, the deformation under load makes the contact surface become a circular from a point between two spheres.
- Physical conditions
  Since the material is a linear elastic body, the variation of the compressive stress on the contact surface with the contact objects is linear relationship. This means that the pressure stress is maximum at the center of the contact surface where the strain is maximum, i.e., $q_0 = q_{\max}$.
- Static equilibrium conditions

The contact surface pressure force which can be obtained from the compressive stress should be equal to the external load.

According to the conditions of the above three aspects, the radius of the circle of the two balls, contact surface (a) and the maximum pressure of center of the load (q_0) and the relative displacement of the two sphere (δ).

$$\mathrm{a} = \sqrt[3]{\frac{3}{4}\frac{R_1R_2}{R_1+R_2}\left(\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}\right)P} \tag{2.71}$$

$$\delta = \sqrt[3]{\frac{9}{16}\frac{R_1+R_2}{R_1R_2}\left(\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}\right)^2 P^2} \tag{2.72}$$

$$q_0 = \sqrt[3]{\frac{9}{\pi^3}\left(\frac{R_1+R_2}{R_1R_2}\right)^2\frac{P}{\left(\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}\right)^2}} \tag{2.73}$$

R_1 and R_2 are the radii of the circle of the two balls; E_1, E_2, μ_1 and μ_2 are the elastic constants; P is the external load.

- The bending of triangular sheet

A simply supported equilateral triangular sheet is bent by evenly distributed moment (M) of the outer perimeter. At present, the deflection surface equation of nonporous continuous triangular plate is

$$\omega_0(x,y) = \frac{M}{12CD}\left(x^3 - 3cx^2 - 3xy^2 - 3cy^2 + 4c^3\right) \tag{2.74}$$

$3c$ is the height of triangular sheet. The corresponding functions $\varphi^0(z)$ and $x^0(z)$ are

$$\varphi^0(z) = -\frac{Mz}{4D} \tag{2.75}$$

$$x^0(z) = -\frac{M}{120}\left(\frac{z^3}{c} + 4c^2\right) \tag{2.76}$$

If a hole is opened in the triangular sheet arbitrarily, and the geometric center is located at the center of the sheet, we can get $\varphi_1(z)$ and $\chi_1(z)$ from function $\varphi^0(z)$ and $\chi^0(z)$. Finally, $\varphi_1(z)$ and $\chi_1(z)$ form as well as the moment (M_θ) formula of the perimeter of the board inside the hole.

Such a circular hole inside the board is

$$\varphi_1(\zeta) = \frac{MR}{4D}\left[\frac{R}{c}\frac{1-\mu}{3+\mu}\zeta^2 - \frac{1}{\zeta}\right] \tag{2.77}$$

$$x_1(\zeta) = -\frac{MR^2}{4D}\left[\frac{2}{3}\frac{R}{c}\frac{1-\mu}{3+\mu}\zeta^3 - \frac{2(1+\mu)}{1-\mu}\ln\zeta - \frac{R}{3c}\frac{1}{\zeta^3} - \frac{4c^2}{3R^2}\right] \tag{2.78}$$

$$M_\theta = M\left[(1+\mu) + \frac{2(1-\mu^2)\cos 3\theta}{3+\mu}\frac{R}{c}\right] \tag{2.79}$$

When $\mu = 0.3$, the bending moment (M_θ) of the perimeter of the circular can be calculate by the function above. While θ equals 0 degree; M_θ reaches the maximum value of 1.355 M. While$\theta = 0^0$, $M_\theta = 1.245$ M.

Method of reduce concentration factor

In mechanical engineering, understanding of the stress concentration factor in various cases is very important. How to improve the structure and to obtain the best design of the intensity is a significant subject.

Here, some methods to reduce the concentration factor have been summarized:

- Improve the geometry of the mechanical parts, such as avoid using sharp corners, employ streamlined or double-curvature line, and increase the radius of curvature of the arc transition appropriately.
- Select the location of the openings properly. In this case, two basic principles should be considered. One is the stress distribution of object; the hole should be opened in the lower stress area of the body. Another is the stress concentration factors and interference of the object; the presence of the stress concentration factor will not lead to the increase in stress caused by the mutual interference of the object.
- To select the appropriate direction of apertures based on the load. Even if the form is different, such as elliptical hole, rectangular hole, or polygon hole, and the orientation of the stress concentration in the location of the stress direction is different, the stress concentration becomes a variant.

- Strengthen local side of the hole. With the increase in the thickness of the strengthening ring, the stress concentration factor declines rapidly.
- Increasing openings or rounds in the low-stress near the stress concentration position
- Using chip-off method. To slash a certain thickness of material in the vicinity the area of stress concentration can make the stiffness of the slashing site decrease and the burden of the area to increase. Thus, the concentration factor decreases.
- Using filling method. When the round holes or grooves are no longer needed, we can fill them up with welding method and eliminate the root of the stress concentration.
- Prestressed method. Before adding load formally, plus some static load which can make part of the structure or most of the produce exceed the yield limit stress and then remove the pre-load, and finally produce residual stresses. This process is referred to as the prestressed method.

All the methods above can be used to reduce the stress concentration factor. But we should choose the methods according to the actual situation.

2.1.3 Fluid Mechanics

2.1.3.1 Introduction

Fluid mechanics studies the fluid equilibrium and macroscopical motion law, the pressure distribution, velocity contour, energy loss, and interface reaction between the fluid and the solid which are the main targets of fluid mechanics; flow around a body or inside a channel is always concerned with the tokamak, and the fluid itself or the impact force from the fluid to the solid wall needs consideration during the design and operation. Generally, there are three studying methods:

- Analytical analysis method: the critical issue of the problem is extracted and an analytical model is built; then the model is described by a series of equations, as well as the boundary conditions and initial status; after the solution of these equations the results are compared with the experimental reality to judge the effectiveness of the theory. This method is based on accurate deduction and could catch the nature of the problem, but due to the lack of many secondary issues, it is suitable to summarize the critical rules, but cannot deal with complicated engineering cases. Therefore, this method is always considered as a guideline.
- Experimental study method: similarly, this method needs to recognize the critical issue, choose proper test fluid and design the test model following the similarity principle. The flowing parameters like velocity, pressure, and flow rate are tested; then they are summarized into dimensionless numbers to fit

general cases. This method has the strongest persuasion, and can be considered as the final confirmation of the problem assumption. However, the accuracy depends not only on the similarity principle which defines the relationship between the test model and the reality, but also on the facility build-up and instrumentation precision. Some extreme problems like atmospheric circulation and fusion plasma movement cannot be simulated in a lab. This method is quite expensive and has low adjustability.

- Numerical simulation method: this method could be considered as the extension of the analytical method when the equation sets are defined, and the boundary condition and the loads are clarified. Numerical methods like difference method or finite element method could be used to get the closest numerical solution to the reality. Compared to the analytical method, this way could solve complicated engineering problems with many details, and for the experiment method, the numerical plan could test numerous plans with quite low time and financial cost. However, this method needs preliminary analytical and experimental work to confirm the numerical model.

2.1.3.2 Basic Formula

To an incompressible, incoherent fluid which is only under gravity and gets static status, a basic formula at any point is defined as

$$\mathrm{z}+\frac{p}{\rho g}=C \text{ or } z_1+\frac{p_1}{\rho g}=z_2+\frac{p_2}{\rho g} \tag{2.80}$$

where z is the vertical position inside the fluid m; p the local pressure Pa; ρ the fluid density kg/m^3; g the standard earth gravity kgm/s^2; and$C$ a constant. This formula is useful to get the hydrostatic pressure on the fluid container.

If the fluid is steadily flowing with adiabatic boundary conditions, the formula can be modified into

$$\frac{v^2}{2g}+z+\frac{p}{\rho g}=H \text{ or } \frac{v_1^2}{2g}+z_1+\frac{p_1}{\rho g}=\frac{v_2^2}{2g}+z_2+\frac{p_2}{\rho g} \tag{2.81}$$

where v is the fluid velocity m/s; and H another constant. This formula is used to calculate the pressure components, including static pressure, dynamic pressure, and total pressure. These two formulas are the basis of testing pressure and velocity of a fluid inside a container or a channel, then the flow rate can be calculated; if the viscosity of the fluid cannot be ignored, a friction dissipation item h_w should be added into the formula, and it becomes

$$\frac{v_1^2}{2g}+z_1+\frac{p_1}{\rho g}=\frac{v_2^2}{2g}+z_2+\frac{p_2}{\rho g}+h_w \tag{2.82}$$

The similarity principle is critical in order to set up an experiment facility; generally there are three principles, the geometry similarity, movement similarity, and dynamic similarity. The first one means the characteristic length of the model and the real case should be proportionable, like the diameter and length; the second asks for the same distribution of the fluid movement and scaled velocity; and the third means the force on the fluid particles has the same direction and proportionable magnitude.

The energy loss in a piping system can be divided into two categories, one is called linear loss, which increases with the pipe length, and can be described as

$$h_f = \lambda \frac{L}{d} \frac{v^2}{2g} \tag{2.83}$$

where h_f is the linear loss height m; λ the loss coefficient, dimensionless; L and d are the pipe length and inner diameter respectively, m; v the velocity m/s; and g the standard earth gravity m/s^2.

The other type of power loss is local loss due to bends, transition sections, and valves, it is described as

$$h_j = \xi \frac{v^2}{2g} \tag{2.84}$$

where h_j is the local loss height m; ξ the loss coefficient, dimensionless; the following part is the dynamic pressure of the fluid, the same as the formula above.

For viscous fluid, a dimensionless Reynolds number is defined to separate flow states into laminar and turbulent flow

$$\mathrm{Re} = \frac{\rho v d}{\mu} \tag{2.85}$$

where ρ is the density of the fluid kg/m^3; v the flow velocity m/s; d the character dimension of the flow channel m; andμ the dynamic viscosity Pa s.

In the laminar flow, the linear loss is only related to the Reynolds number, which follows the equation of

$$\lambda = \frac{64}{\mathrm{Re}} \tag{2.86}$$

For the turbulent flow, the linear loss can be calculated with the equation below as

$$\frac{1}{\lambda^{1/2}} = 2lg \frac{d}{2\varepsilon} + 1.74 \tag{2.87}$$

where ε is the roughness of the all, m.

There is also a complete experimental study for the linear pressure drop, which is more accurate and convenient in the real application.

The experimental energy loss curve is also divided into the laminar section, Re $<$ 2320, which uses the same formula above, and in the turbulent section, the latter is further divided into four sections:

Transition section from laminar flow to turbulent, 2320 $<$ Re $<$ 4000, the state is not steady, and the energy loss is

$$\frac{1}{\lambda^{1/2}} = -2\,\mathrm{lg}\left(\frac{\varepsilon}{3.71d} + \frac{2.51}{\mathrm{Re}\lambda^{1/2}}\right) \tag{2.88}$$

Turbulent smooth pipe section, $4000 < \mathrm{Re} < 26.98\left(\frac{d}{\varepsilon}\right)^{8/7}$, the flow state is turbulent, but the wall roughness is still thinner than the viscous layer, and the loss coefficient is

$$\lambda = \frac{0.3164}{\mathrm{Re}^{0.25}} \tag{2.89}$$

In turbulent smooth to rough wall transition section, $26.98\left(\frac{d}{\varepsilon}\right)^{8/7} < \mathrm{Re} < 2308\left(\frac{d}{\varepsilon}\right)^{0.85}$, the viscous layer gets thinner, and the roughness has more impact, thus the loss coefficient is

$$\lambda = 1.42\left[lg\left(\mathrm{Re}\frac{d}{\varepsilon}\right)\right]^{-2} \tag{2.90}$$

For total rough section, $2308\left(\frac{d}{\varepsilon}\right)^{0.85} < \mathrm{Re}$, the fluid viscosity does not have impact on the energy loss, the linear pressure drop is related to the roughness, and the formula can use the one above:

$$\frac{1}{\lambda^{1/2}} = 2lg\frac{d}{2\varepsilon} + 1.74 \tag{2.91}$$

When the fluid flows from a thin pipe to a thick one, the energy will be exhausted in the eddies, and the local loss coefficient can be calculated from

$$\xi_1 = \left(1 - \frac{A_1}{A_2}\right)^2 \text{ or } \xi_2 = \left(\frac{A_2}{A_1} - 1\right)^2 \tag{2.92}$$

where A_1 and A_2 are the section area of the thin pipe and the thick one, respectively, and the ξ_1 and ξ_2 are the loss coefficients.

On the contrary, when the fluid enters a thin pipe from a large volume, there are also complicated eddies, but the energy loss is different, which has an additional part of contraction loss, and follows the equation below:

$$\xi = \frac{\xi_c}{C_c^2} + \left(\frac{1}{C_c} - 1\right)^2 \tag{2.93}$$

where $C_c = \frac{A_c}{A_2}$ is the contraction coefficient of the flow.

2.1.4 Heat Transfer

2.1.4.1 Introduction

The temperature range in the tokamak represents the limits of human science, the superconducting system, which works at nearly absolute zero degree, and the fusion reaction, which occurs at a billion degree, existing in the same machine; because the power that drives heat transfer has temperature difference, the heat transfer is strong and important.

The main task of the heat transfer calculation is to get the rules of the heat movement, and the temperature distribution, which is also the reason for thermal stress, a prime structural load in tokamaks. Generally speaking, there are three typical applications:

- Heat transfer enhancement in which the heat flux should be maximized to meet the requirement of limited temperature difference, component volume, and pumping power.
- Thermal insulation, in which the heat flux should be minimized to lower the heat load to the cryogenic system and increase the feasibility and economic efficiency.
- Temperature control, in which the temperature at certain locations should be maintained at a preset level to keep the instrumentation status or prevent high thermal stress.

There are three heat transfer types: conduction, convection, and radiation.

- Conduction occurs between touching objects, there is no relative slide, and the heat transfer is performed by micro particles like molecules, atoms, and electrons.
- Convection exists on the interface between fluid and solid and can be separated into cooling and heating problems according to the temperature change of the fluid. There are natural and forced convections; both are considered in the tokamak design.
- Radiation does not need transfer media, which determines it as the only heat transfer type in vacuum, where there are no touching objects or fluid–solid interfaces, and this is what is there in the modern superconducting tokamaks.

2.1.4.2 Basic Formulas

Heat conduction follows the Fourier's law, which defines the heat flow through an area proportionable to the material conductivity and the cross area, and driven by the temperature gradient in the conduction path

$$\Phi = -\lambda A \frac{\partial t}{\partial x} \tag{2.94}$$

where λ is the conductivity W/mK; t the temperature K; A the cross-section area m^2; and x the conduction path coordinate m.

Based on Fourier's law, a general conduction equation is defined, which also considers the transient effects

$$\rho c \frac{\partial t}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial t}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial t}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda \frac{\partial t}{\partial z}\right) + \dot{\Phi} \tag{2.95}$$

where ρ is the material density kg/m^3; c the specific heat J/kgK; τ the time s; and $\dot{\Phi}$ the heat generation inside the volume W/m^3.

This equation can be simplified into a Laplace formula when there is no internal heat source in a steady-state problem with constant material properties

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} = 0 \tag{2.96}$$

If the problem can be further simplified into unidimensional, then only one item is left on the left, which is easy to solve.

To solve these conduction equations, three types of boundary conditions are defined:

First type: Dirichlet boundary condition, constant temperature at the boundary.
Second type: Neumann boundary condition, constant heat flux at the boundary.
Third type: Robin boundary condition, convection heat transfer coefficient between the solid and the fluid, as well as the fluid temperature.

To a unidimensional multi-layer conduction problem, the heat flux through the wall can be described as

$$q = \frac{t_1 - t_{n+1}}{\sum_{i=1}^{n} \frac{\delta_i}{\lambda_i}} \tag{2.97}$$

where q is the heat flux W/m^2; t_1 the temperature on the first wall K; t_{n+1} the temperature on the last wall K; n the number of the layers, dimensionless; δ_i the thickness of the i layer m; andλ_i the conductivity of the i layer W/mK.

For a cylindrical wall, a similar formula is deduced as

$$q = -\lambda \frac{\mathrm{d}t}{\mathrm{d}r} = \frac{\lambda}{r} \frac{t_1 - t_2}{ln\left({}^{r_2}/_{r_1}\right)} \tag{2.98}$$

where r is the radius of the cylinder at any position m; r_1 and r_2 are the inner and outer radius m.

For a spherical wall, the heat flow formula is

$$\Phi = \frac{4\pi\lambda(t_1 - t_2)}{{}^{1}/_{r_1} - {}^{1}/_{r_2}} \tag{2.99}$$

The control equations of the convection heat transfer are similar to the fluid dynamics, which consist of three parts:

First part: continuity equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{2.100}$$

Second part: Navier–Stokes equation

$$\rho\left(\frac{\partial u}{\partial \tau} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = F_x - \frac{\partial p}{\partial x} + \eta\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{2.101}$$

$$\rho\left(\frac{\partial v}{\partial \tau} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = F_y - \frac{\partial p}{\partial y} + \eta\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \tag{2.102}$$

Third part: energy equation

$$\frac{\partial t}{\partial \tau} + u\frac{\partial t}{\partial x} + v\frac{\partial t}{\partial y} = \frac{\lambda}{\rho c}\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2}\right) \tag{2.103}$$

where u and v are the fluid velocities in x and y directions; F_x and F_y are the forces in these two directions.

These formulas are difficult to solve, and some experimental equations are summarized for easy application.

For the forced turbulent convection inside a pipe, the heat transfer coefficient h can be calculated by Gnielinski equation

$$\mathrm{Nu} = \frac{(f/8)(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7\sqrt{f/8}\left(\mathrm{Pr}^{2/3} - 1\right)}\left[1 + \left(\frac{d}{l}\right)^{2/3}\right]c_i \tag{2.104}$$

where $\mathrm{Nu} = hd/\lambda$, $\mathrm{Re} = ud/\upsilon$, $\mathrm{Pr} = \mu c/\lambda$ are dimensionless numbers; $f = (1.82lg\mathrm{Re} - 1.64)^{-2}$ is the Darcy resistance coefficient; $c_i = \left(\mathrm{Pr}_f/\mathrm{Pr}_w\right)^{0.01}$ for liquid, and $c_i = \left(T_f/T_w\right)^{0.45}$ for gas.

For the laminar convection inside a pipe, the Nu number is a constant which is related to the channel shape and heating boundary conditions; for example, for a circular pipe under a constant heat flux, the Nu number is 4.36; while under constant wall temperature, it is 3.66; these two values change to 3.61 and 2.98 for a square pipe.

In the case that fluid flows over a pipe, the heat transfer coefficient can be calculated as

$$\mathrm{Nu} = 0.3 + \frac{0.62\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}}{\left[1 + (0.4/\mathrm{Pr})^{2/3}\right]^{1/4}}\left[1 + \left(\frac{\mathrm{Re}}{282000}\right)^{5/8}\right]^{4/5} \tag{2.105}$$

For natural convection in a big room, the heat transfer coefficient can be got from

$$\mathrm{Nu} = C(\mathrm{GrPr})^n \tag{2.106}$$

where $\mathrm{Gr} = \frac{g\alpha_v \Delta t^2 l^3}{\upsilon^2}$ is another dimensionless number; C and n are two constants which depend on case, for example, to a vertical flat plate in laminar flow $C = 0.59$ and $n = 0.25$; when the flow is turbulent $C = 0.11$, and $n = 1/3$.

The basic equation of radiation heat transfer is the Stefan-Boltzmann law for an ideal black body

$$E = \sigma T^4 \tag{2.107}$$

where E is the radiation power W; σ the black body radiation constant, and 5.67×10^{-8} W/(m^2 K^4).

The radiation heat transfer is affected by the surface's shape and location in a radiation pair, this geometry parameter is called angle factor. The only material property that has impact is the emissivity, which defines the grayscale.

The radiation heat transfer between every two surfaces can be calculated from the formula

$$\Phi_{1,2} = \varepsilon A_1 X_{1,2}(E_{b1} - E_{b2}) \tag{2.108}$$

where $\Phi_{1,2}$ is the radiation from surface #1 to #2, W; ε the surface emissivity; A_1 the surface #1 area, m^2; $X_{1,2}$ the angle factor from surface #1 to #2; E_{b1}, and E_{b2} are the black body radiation power of surface #1 and #2, W/m^2.

If the surface #1 is flat or projecting, no radiation will return to #1, and the radiation formula is modified as

$$\Phi_{1,2} = \frac{A_1(E_{b1} - E_{b2})}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\varepsilon_2} - 1\right)} \tag{2.109}$$

If the two surfaces have a similar area, the formula can be simplified into

$$\Phi_{1,2} = \frac{A_1(E_{b1} - E_{b2})}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{2.110}$$

If surface #2 has a much bigger area than #1, then the formula becomes

$$\Phi_{1,2} = \varepsilon_1 A_1(E_{b1} - E_{b2}) \tag{2.111}$$

2.1.5 Electromagnetics

2.1.5.1 Introduction

Electromagnetism is the study of the interaction between electricity and magnetism phenomenon. According to the viewpoint of modern physics, magnetic phenomenon is produced by charge in motion, and thus in electricity within some magnetism contents.

According to modern physics, the electric and magnetic fields are intertwined.

Electric field: Charge as research object is studied in the field. It includes the movement of the charge in the electric field, the interaction between the charges, and a constant current generated by an electric field.

There are three basic theorems to solve electrical problems:

- Gauss's law of electric field: Electric flux density of the electric field at a point equals to the electric field strength.
- Circuital law of electrostatic field: In any electrostatic field, the circulation along any circuit is zero.
- Kirchhoff's law: (1).the current flowing out from the node is equal to the one which flows in. (2). Along the circuit, the sum of electromotive forces is zero.
- Magnetic field: Current or moving charges generate magnetic field in their surroundings, and the magnetic field can exert a force to its surrounding current or moving charges.

There are three basic theorems to solve magnetic problems:

- Ampere's law : The direction of the closed path is in right-hand rule with the direction of the normal to the area S. The circulation of B along a closed path L is equal to the current enclosed by L.
- Gauss's law of Magnetic field: The magnetic flux through any enclosed surface in the magnetic field equals zero.
- Ampere circuital law: In a constant magnetic field, the circuital current along any enclosed path L, is equal to μ_0 times the sum of currents through this closed path.

2.1.5.2 Basic Formula

Summarizing electromagnetic theory, there are four main formulas:

- Gauss's law of Electric field: The integral form of Gauss Law is a relation between the flux of E through any closed surface S, and the total charge Q enclosed by S. The flux of E through the surface S of V equals the total charge Q enclosed by S divided by a constant $\in_0$.

$$\oiint_s E \cdot \mathrm{dS} = \frac{1}{\in_0} \iiint_{\mathrm{v}} (\rho + \rho')\mathrm{dV} = \frac{Q}{\in_0} \tag{2.112}$$

where E is electric flux intensity, V/m; $\in_0$ the constant; Q the total charge, C;

- Circuital law of Electric Field:

$$\oint_L E \cdot \mathrm{dl} = -\iint_S \frac{\partial B}{\partial t} \cdot \mathrm{dS} \tag{2.113}$$

where E is the electric flux intensity V/m; B the magnetic flux density T; and t the time s.

- Gauss's law of Magnetic field:

$$\oiint_s B \cdot \mathrm{dS} = 0 \tag{2.114}$$

Where B is the magnetic flux density T;

- circuital law of magnetic field:

$$\oint_L B \cdot \mathrm{dl} = \mu_0 \iint_s (\mathrm{j} + \mathrm{j}^{'} + \frac{\partial D}{\partial t}) \cdot \mathrm{dS} \tag{2.115}$$

Where B is the magnetic flux density T; μ_0 the constant; A; $j,j^{'},\frac{\partial D}{\partial t}$ the current A.

2.1.5.3 Law of Electromagnetic Induction

There are two main reasons for the phenomenon of electromagnetic induction. First, the magnetic field's change; second, conductor and magnetic field occurs relative motion.

Lenz's Law determines the direction of induced current. Lenz's Law can be described as the direction of induced current in the closed circuit. It always makes the magnetic flux generate by itself hindering the change of induced current's magnetic flux

Lenz's Law can be expressed by the formula

$$\varepsilon \propto -\frac{\mathrm{d}\phi_B}{\mathrm{d}t} \tag{2.116}$$

Where ε is induced electromotive force V; ϕ_B the magnetic flux, Wb. t time, s.

2.1.5.4 Self-inductance and Mutual Inductance

Self-inductance: When the current flowing through the coil changes, the magnetic flux through the coil also changes, thus coil generates induced current, the induced current hinders the change of the original current, and makes the change of original current slowdown. It can be expressed by the formula

$$\varepsilon^{'} = -L\frac{\mathrm{d}I}{\mathrm{d}t} \tag{2.117}$$

Where $\varepsilon^{'}$ is self-induction electromotive force V; L the coefficient of self-inductance H; I the current A; t time s. Mutual inductance is when a coil's current changes, an induced electromotive force and an induced current will be generated in another coil around. It can be expressed by the formula

$$\varepsilon_{12} = -\frac{\mathrm{d}\phi_{\mathrm{B12}}}{\mathrm{d}t} = -M_{12}\frac{\mathrm{d}I_1}{\mathrm{d}t} \tag{2.118}$$

$$\varepsilon_{21} = -\frac{\mathrm{d}\phi_{\mathrm{B21}}}{\mathrm{d}t} = -M_{21}\frac{\mathrm{d}I_2}{\mathrm{d}t} \tag{2.119}$$

where ε_{12} and ε_{21} are induced electromotive forces V; $M_{12}$and M_{21} are coefficients of mutual inductance H; I_1 and I_2 are currents A.

2.2 Code and Standard

2.2.1 Introduction

The construction of a tokomak is a complicated project which includes kinds of activities. To ensure the quality of every step, rigorous standards should be set up to guide the design, manufacture, assembly, operation, and retirement process. So far there is no mature standard for the tokamak, though the standard system for general machinery and the fission industry has a long history and could be referred to in the fusion reactor project. For example, the cryostat is a vacuum chamber and can be designed following the ASME BPVC (Boiler and Pressure Vessel) or Chinese GB150 &151; the bellows could refer to the EJMA (Expansion Joint Manufacturers Association) standard; and the cryogenic pipes should pass the EN13480 standard. There are still a lot of new standards to be developed to satisfy the special requirements of the tokamak. In the following sections, American and French nuclear standards are briefly introduced, and the standard development with ITER project.

2.2.2 American Nuclear Standard

The USA has complete fission standard system, besides the national laws and government rules, ANSI (American national standard institute), ASME (American society of mechanical engineers), and ANS (American nuclear society) which take the main responsibility for standard setting. The American nuclear standard is also the basis of the international nuclear standard.

There are four levels in the American nuclear standard:

First: atomic energy Act made by Congress;
Second: the 10th Section of the CFR (Code of Federal Regulation);
Third: R1G made by the NRC (Nuclear Regulatory Commission);
Fourth: main body of the application standards.

Some typical standards in the main body are listed below, and their application fields are introduced:

ANS 2 series: nuclear island location selection;
ANS 51, 56-59 series: nuclear island system;
ASME AG, NOG, NUM, QME, BPVC: nuclear island machinery equipment;
ANS 57 series, ASTM: nuclear power plant fuel;
IEEE: control system and electrical equipment;
ACI (American concrete institute), AISC (American institute of steel construction), ASCE (American society of civil engineers), ASME: safety-related civil engineering;
ASTM, ASME BPVC: nuclear and conventional island equipment and materials;
ASME, general standard: nonsafety-related system and equipment;
ASME, OM, SPG, N511: in-service check and test;
RG11 188, NUREG-1800: aging management and maintenance;
ANS 3 series: emergency;
RG11159: retirement.

2.2.3 French Nuclear Standard

The French nuclear reactor project is based on the American standards in early time, then AFCEN (French society for design and construction and in-service inspection rules for nuclear islands) set up a series of French RCC (Règles de Conception et Construction Mécanique Rapide) standards, which integrate the ASME III experience and national conditions. Compared to American standards, RCC series are more systematic and easy to apply.

The levels of French standards are similar to the American experience. The main body includes seven parts:

RCC-M: mechanical components of PWR (Pressurized water reactor) nuclear islands;
RCC-MR: mechanical components of FBR (Fast breeder reactors) nuclear islands;
RCC-C: fuel assemblies for PWR power plants;
RCC-E: electrical components of power plants;
ETC-C/RCC-G: civil engineering in PWR nuclear islands;
RSE-M: in-service inspection rules for components of PWR nuclear islands;
ETC-F: rules of design and construction for fire protection of the EPR (European Pressurized Reactor).

2.2.4 Fusion Project Standard

Fusion devices have many differences with fission reactors, for example, the fusion process and superconducting components are integrated in one tokamak; there is a complicated magnetic field and strong EM (electromagnetic) force on the coils and other metal components like vacuum vessel, radiation damage from the high energy neutron from the fusion reaction are applied to the PFC (plasma facing component) materials. Therefore, a lot of work should be performed to set up the tokamak standard.

RCC-MR is a representative effort in this field. Its function is to define design and construction rules for mechanical components of nuclear installations applicable for high temperature structures and ITER vacuum vessel. It comes from the merging of RCC-MX and RCC-MR.

RCC-MR includes five sections, and there are seven subsections in Section 1:

Section 1: nuclear installation components;

Subsection A: general;
Subsection B: class 1 components
Subsection C: class 2 components
Subsection D: class 3 components
Subsection H: supports
Subsection K: examination and handling mechanisms
Subsection Z: technical appendices

Section 2: materials;
Section 3: examination methods;
Section 4: welding;
Section 5: fabrication.

The largest fusion program ITER (International thermonuclear experimental reactor) is a milestone in fusion history. It contributes standard efforts, like the magnet structural design criteria, which are applied to the magnet components within the cryostat and is divided into four sections:

Part I: includes the main structural components and gives the background to the choice of many of the criteria used in Parts II, III, and IV;
Part II: includes the TF, CS, PF, and CC winding packs, conductors, high and low voltage insulation, and epoxy fillers;
Part III: includes bolts, keys, supports, and special components;
Part IV: includes cryogenic piping.

These efforts consider the difference between tokamaks and previous fission reactors, and make modification or add new criterions to guide the design and construction of fusion devices.

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