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Extreme Pressure Equipments

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Abstract: Pressure equipments in the process industries and the newly developing industries usually have extreme sizes and/or are subjected to extreme operating conditions such as high pressure, blast loading, cryogenic temperature, elevated temperature, complex corrosion, and so on. In order to understand, research and develop these equipments systematically, a concept of extreme pressure equipments(EPEs) is proposed in this paper. The applications and demands of EPEs in petrochemical industry, coal chemical industry, advanced energy, military, space technology, and environment protection are introduced. Basic scientific problems in material, design, inspection, and safety related to EPEs are discussed. Then, take chemical composition, manufacturing process, service duration, and operating conditions for example, main factors which affect material properties of EPEs are analyzed. New design concepts including design based on life cycle, dynamic design and light-weight design are introduced. EPEs with higher efficiency, lower cost and safer performance are in urgent demand in national major projects including ten million ton oil refinery, one million ton ethylene, liquefied natural gas transportation, and nuclear power plant. Thus, further research should be conducted on information acquisition, multi-mechanism damage coupling model, damage inspection, life prediction, online safety monitoring, maintenance strategy, safety pre-warning system, and emergency system.

Key words: pressure equipment, pressure vessel, pressure pipe

1 Introduction*

Pressure equipments in the process industries and the newly developing industries usually have extreme sizes in diameter, height, weight, thickness, volume, and/or are subjected to extreme operating conditions such as high pressure, blast loading, cryogenic temperature, elevated temperature, complex corrosion, and so on.

In order to understand, research and develop these equipments systematically, a concept of extreme pressure equipments(EPEs) is proposed in this paper. EPEs are those pressure equipments with extreme sizes and/or under extreme operating conditions.

Compared with the ordinary pressure equipments, EPEs are capital-intensive and have more difficulties in design and manufacture. The failure of EPEs may cause not only leak and explosion, but also fire, poisoning and stop of production, which may cause heavy casualties, economic loss and environmental pollution. The manufacturing level of EPEs is also an important symbol to measure the national manufacturing capacity, which is related to the national economy, state security and social stability. The extremalization of pressure equipments is also playing an important role in the future trend of manufacture industry[1].

As the key equipments, EPEs are in high demand in various industries, such as petrochemical industry, coal chemical industry, energy industry, military, space technology, environment protection, and so on. The scope and applications of EPEs will be expanded with the development of science and technology. The acquaintance and research on EPEs have great significances and should be considered as a long-term strategic object in order to ensure the long-term safe operation of EPEs.

In this paper, the demands of EPEs from various industries are presented in section 2, and the basic scientific problems on material science, design technology, inspection and safe technology of EPEs are discussed in section 3, which is then followed by some concluding remarks in section 4.

2 Demands of EPEs

Due to the special sizes and applications, EPEs have attracted more and more attentions from all over the world. In China, several important programs and plans have been established and implemented for the national key projects, e.g. advanced energy, advanced manufacturing, large scale assemblies of megaton ethylene and coal chemical industry[2]. The urgent demands could be steady foundation, unprecedented chance and challenge for the development of EPEs. The main demands of EPEs in petrochemical

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industry, coal chemical industry, energy industry, military, space technology, and environment protection are presented in the following sub-sections.

2.1 Petrochemical industry and coal chemical industry

EPEs are widely used in petrochemical industry and coal chemical industry, which are always parts of the most traditional and important industries. With the development of design and manufacture technology, more and more large scale equipments with extreme sizes are needed in the process industries. For example, the mass of direct coal liquefaction reactor has reached to 2 800 t; the height of tower equipment has reached to 130 m, the thickness of pressure vessel has reached to 400 mm, and the diameter of PTA oxidation reactor has reached to 9 m.

2.2 Energy industry

The consumption of fossil power may cause the lack of resources and serious environmental pollution, thus the advanced energy is urgently needed. The demands and developments of energy are considered to be the major drivers and milestones in pressure vessel technology[3].

2.2.1 Nuclear power

Nuclear power is one kind of safe, clean, stable, and economical energy which can be supplied in large scale. The nuclear fission reactor produces heat through a controlled nuclear chain reaction in a critical mass of fissile material[4]. As one of the most important equipments in the nuclear power plant, the reactor is working under extreme conditions such as high temperature, high pressure, high radiation, and highly corrosive environment. For example, when the water in pressurized water reactor(PWR) is heated to the high temperature of 300–330℃, the working pressure of PWR should be as high as 12.2–16.2 MPa, which can prevent the water in PWR from boiling.

2.2.2 Hydrogen energy

Hydrogen, thanks to its renewable and pollution-free characteristics, has become the most potential energy carrier in the future. However, the hydrogen storage and transportation are the bottleneck for the development of hydrogen energy[5].

High-pressure hydrogen storage is the most available and highly developed method for commercialization, which has the advantages of high efficiency, low cost, and technical simplicity[6–8]. With the comprehensive consideration of the energy consumed in compression, the endurance mileage and the investment of the infrastructure construction, the appropriate pressure of the tanks for on-board hydrogen storage is generally as high as 35–70 MPa. The pressure of stationary hydrogen storage vessels in hydrogen refilling stations should be 40–75 MPa in order to ensure fast-filling of hydrogen. Hydrogen embrittlement should be considered in the material selection for such vessels or containers.

2.2.3 Supercritical and ultra supercritical power

In recent years, a positive progress has also been made in clean and efficient coal fired power generation technology. In China, the design and manufacture of 600 MW class ultra supercritical power generation units have been mastered, while several 1 000 MW class ultra supercritical power generation units are still in operation or under construction[9]. The pressure of the main steam in ultra supercritical power generation units would reach to 25–35MPa, while the temperature of the main steam and the reheated steam could be higher than 650℃. Further advanced steam conditions of 700℃ and above have already been initiated in order to achieve a higher efficiency[10–11].

2.2.4 Liquefied natural gas storage and transportation

Along with the adjustment of Chinese energy structure, the usage and demand for natural gas are increasing rapidly. A great number of pipes and cryogenic vessels with large size and light weight are needed by the transportation and storage of natural gas. The volume of the liquefied natural gas tank with temperature of −162℃ has reached to 200 000 m^3, and a larger tank, which has the volume of 250 000 m^3, is under construction in Japan.

2.3 Military and space technology

EPEs also play an important role in the military technology. For example, explosion containment vessels (ECVs) have been extensively employed to contain the effects of explosion shock waves and products, to protect personnel and experimental equipments, to recycle test products and to prevent environmental contamination[12]. Blast load increases very quickly, which has a high peak value (up to 400 MPa), a high strain rate (10^2–10^3 s^{-1}) and a short duration. In the research and design (R&D) of ECVs, not only the influence of strain rate on the material and the structure but also the inertial effect should be taken into account[13].

To explore and utilize the outer space, more and more attention has been paid to the space technology. The liquid hydrogen and liquid oxygen, which provide fuel for the rocket engine, satellite and spacecraft, must be stored in high pressure cryogenic vessels. For example, in the performance test of the rocket engine, the high pressure cryogenic vessels for liquid hydrogen under extreme conditions with the design pressure up to 40 MPa, and the design temperature down to −253 ℃.

2.4 Environment protection

Environmental pollution around the world is becoming more and more serious. The disposal of various harmful wastes (such as wastewater and sludges) is one of the key parts and the bottlenecks for the environmental protection.

Supercritical water oxidation(SCWO) technology presents important environmental advantages for the treatment of industrial wastes and sludges[14]. The SCWO process should be operated under the pressure of 30–40

MPa, and the temperature of 400–700℃. But the corrosion of wastewater and sludges is much more serious under such extreme pressure and temperature, which could cause difficulties in the material selection, design and manufacture for the equipments used in SCWO.

3 Basic Scientific Problems of EPEs

Because of the extreme sizes and operating conditions, the development of EPEs is facing more difficulties than the ordinary pressure equipments. To ensure safer performance of EPEs, more attention should be paid to the material, design, inspection, safety technology, and so on. Those basic scientific problems are discussed in the following parts.

3.1 Material science of EPEs

Good material properties of EPEs should be guaranteed to ensure the safety in the whole life. The strength and life of material might be influenced by many factors, e.g., chemical composition, manufacturing process, service duration, and operating conditions.

(1) Influence of chemical composition on material properties. Failures of EPEs are always related with ductile degradation due to the impurities in the material. For example, resistance of temper brittleness in hydrogenation reactor, neutron irradiation embrittlement in nuclear reactors, and hydrogen embrittlement in hydrogen storage vessels, increase with the better control of impurities. More attention should be paid to the purification, the smelting, the refining and the homogenization processes in order to obtain a higher purity and quality of steels with high strength.

(2) Influence of manufacturing process on material properties. The manufacturing process, such as heat treatment, welding, and forming (including cold stretching process), could affect the properties of material. For example, the microstructure transformation and property change of material may be caused by the deformation and the residual stress from welding. The influence and its mechanism should be studied, and relevant protection should be presented. Prediction of residual stresses due to welding, post welding heat treatment(PWHT), local PWHT have attracted more and more attention.

(3) Influence of service duration and operating conditions on material properties. The strength and life of material might be degraded by the service duration and the extreme operating conditions, such as high pressure, high temperature, neutron irradiation and multi-phase fluid. The degradation of material properties needs to be studied, and its process, law and mechanism should be explored. The inspection of degradation, as well as the life prediction method should be developed. The databases of basic properties, failure modes and operating conditions should be established so as to facilitate the research.

3.2 Design technology of EPEs

With the developments of mechanics and computer technology, new concepts are introduced to facilitate and optimize the design of EPEs.

(1) Design based on life cycle. Efficiency and safety of EPEs are obviously affected by various factors, such as structure, material and manufacturing process. The traditional R&D process for pressure equipments includes the laboratory, pilot-scale and industrial tests, in which the long time and large cost have limited the R&D speed.

The design of EPEs should consider not only the normal operating conditions, but also the other parts in the life cycle, such as the construction, installation, maintenance and rejection. The objective of design based on life cycle is to enhance environmental performance over the life cycle while also optimizing functional performance and lowering cost[15]. To ensure the safety, stability and high efficiency of the EPEs in the life cycle, simulation methods should be explored on the structural mechanical behaviors under various loading. Further study should be conducted on the multi-scale simulation of transformation and reaction, as well as the coupling of multi-physical field. The innovation design and digitalization technology should be employed in the design based on life cycle, which may help reduce the cost and risk of the experiments and increase the R&D speed of EPEs.

(2) Dynamic design. Due to the adoption of new material, new manufacturing process and the extreme operating conditions, the mechanical behaviors and failure characteristics of EPEs are far beyond the description of the simple and traditional theoretical models.

To ensure the safety and stability of EPEs in the life cycle operation, not only the static loads, but also the dynamic loads, e.g., wind load, earthquake load, crash load and blast load, should be taken into account. Meanwhile, the influence of the fluid movements on material and structure of EPEs should also be considered. The Pressure Vessel Research Council (USA) has established a Committee of Dynamic Analysis and Testing, to analyze the response and the failure law of equipments in the process of natural disasters, wars and impact (e.g., the impact of transportable pressure equipments, the thermal shock, and the water hammer). In addition, special precautions should be added in the design.

(3) Light-weight design. The light-weight design focuses on safety, economics and resource conservation, which is the embodiment of green manufacture and the development trend of the EPE design[1, 16–17]. It is shown that 60% of the fuel in the vehicles is consumed on its tare weight, and reducing 10% of the weight will lead to 6%–8% saving on the fuel.

The light-weight design of EPEs can be achieved by increasing material strength, reducing safety factor, applying cold stretching technology, employing design by analysis method, and optimizing the structure of EPEs[18–19]. Research should be further explored on prediction of plastic collapse load of complicated structure, local failure criteria, and influence of light-weight on manufacture and inspection[20]. In addition, optimization design of multi-physical coupling field, integrated design of material-structure-technology, risk-based design and reliability design are the other concerns in the light-weight design.

3.3 Inspection, monitoring, and maintenance of EPEs

Inspection, monitoring and maintenance are important to reduce the failure risk of EPEs. At present, there are a lot of difficulties in inspecting and monitoring the development of damage and crack propagation. The key technologies of acquisition, extraction and transportation of the characteristic information are still under investigation.

(1) Information acquisition and damage inspection. Inspection methods for the properties and the extent of damage under extreme operating conditions should be developed.

(2) Online safety monitoring. High performance transducer and monitoring method on the deformation, vibration and leakage should be explored. And the system of online safety monitoring, fault diagnosis and pre-warning should be developed based on the inspection data.

(3) Maintenance strategy and life cycle technology. EPEs are normally used as the key equipments in large scale process industries, in which a production stop could lead to a serious economic loss. Therefore, the maintenance should be operated in a strategic way and the life cycle technology of EPEs should be taken into account.

3.4 Safety technology of EPEs

Despite all the problems listed above, the following areas are to be explored as the safety technology of EPEs.

(1) Multi-mechanism damage coupling model of the structure failure. There are various damage mechanisms responsible for the failure of EPEs[21]. Brittle fracture, ductile fracture and the combination of them are the main criterias for the EPEs failure. However, the influence of the multi-mechanism damage coupling on the strength and life has not been sufficiently studied. The structure failure criteria, which include the interaction of creep, fatigue and corrosion, should be developed.

(2) Safety pre-warning system and emergency mechanism. Because of the extreme sizes and/or the extreme operating conditions of EPEs, unplanned outages and hazardous accidents cause huge economic losses, environmental contamination, and human injuries, due to component degradation, exogenous changes, and operational mistakes[22]. In order to ensure the safety and optimize the operational performance and reliability of EPEs, safety pre-warning system should be established to analyze the current safety state of each component and the whole system. The adoption of pre-warning system would be used to indicate hidden hazards and potential consequence, in order to predict future degradation trends in the long term.

Safety assessment, and the emergency mechanism should be established for EPEs on the basis of investigating the consequences and the law of the failures, such as fire, explosion and crash.

Moreover, the system of codes and standards on EPEs is still fragmented and insufficient. More codes and standards should be established in order to satisfy the extreme requirements and provide the guideline for the design, construction, and maintenance of EPEs.

Because of the globalization, there are many challenges and opportunities in the international competition and cooperation. Therefore, the international exchange and cooperation should be enhanced. And the understanding and adoption of codes and standards from different countries and regions should be improved in order to promote the development of EPEs.

4 Conclusions

(1) The concept of EPEs is proposed. The urgent demands from various industries are the major driver for the development of EPEs.

(2) Basic scientific problems on material, design, inspection and safety technology are summarized to be hot spots in further investigation of EPEs. The intersection between EPE technology and other subjects (e.g. mechanics, computer technology, control and digital signal processing) will greatly facilitate the research and application of EPEs.

(3) To satisfy the pressing requirements from national major projects on EPEs with higher efficiency, lower cost and safer performance, further investigation should be conducted on information acquisition, multi-mechanism damage coupling model, damage inspection, life prediction, online safety monitoring, maintenance strategy, safety pre-warning system, and emergency system.

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