PRESSURE VESSELS AND SHELL STRUCTURES

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Key words: Pressure vessel, bottom, flange, nozzle, cover, releasable connection, shell structure, design procedure (scheme), limiting state, verifying calculation, steady-state (static) strength, rigidity, endurance(cyclic load strength), brittle fracture resistance, endurance limit, progressing mechanical shaping, seismic impact, vibration strength.

Contents

Summary

The basic industrial and technical areas of applications of pressure vessels and shell structures use are reviewed. The design and operation features of these structures for chemical and petrochemical production, metallurgy, thermal and nuclear power engineering, shipbuilding, aviation and rocket-aerospace systems are presented. The specifications and operating conditions of pressure vessels are listed depending on the performance type.

The main design elements of pressure vessels, including: cylindrical parts, bodies and casings, bottoms and heads, flanges and necks, covers, nozzles, separable joints, fasteners are discussed. Examples of composite material shell structures in various industrial and technical implementations are given.

The general provisions for strength analysis of pressure vessels and shell structures are formulated on the basis of limit state. The following estimated cases are considered: steady-state (static) strength calculation; stability estimation; endurance and endurance limit calculation; brittle fracture strength calculation; steady-state limit calculation; progressing mechanical shaping estimations; seismic impacts estimation; vibration strength analysis. Underlined are the special features of calculation schemes and procedures relative to pressure vessels, submarine vessels' rigid hulls and aircraft fuselages.

1. Introduction

Throughout the history of human civilization various reservoirs like amphora, jugs, boilers, teapots, tubes and pipes, pressure vessels, etc. have been a very important part of technical and technological systems.

The efficiency and modern technical level of systems, equipment and apparatuses in any industry are determined by a number of quality parameters as follows: reliability, safety, transportability, ergonomics, and technical aesthetics as well as patent-law and ecological parameters. The shell structures comprising: pressure vessels and pressure apparatuses used in power, chemical, machine building industries and agriculture; submarine hulls; fuselages of aircrafts and rocket- space systems; nuclear reactors, etc., - are not an exception. In most cases such structures are operating in the presence of high internal (P_i) and external (P_o) pressures, outside and weight pressures, assembly loads, high and low temperatures (t), aggressive media, increased radiation level or used in the process of hazardous and poisoning substances processing, etc. That is why at the design and operation stages of those structures when using new materials and technologies to provide the increase of reliability, safety and vulnerability level and to enhance the environment protection it is necessary to solve the number of tasks.

2. Areas of Application of Pressure Vessels and Shell Structures

The shell structures and pressure vessels (diameter of 0.1m to 70m, height of 0.5m to 100m) are of wide use in various industrial and technical areas. The design and operational features of some of some of them are considered. The main types of shell like structures are presented in Figure 1.

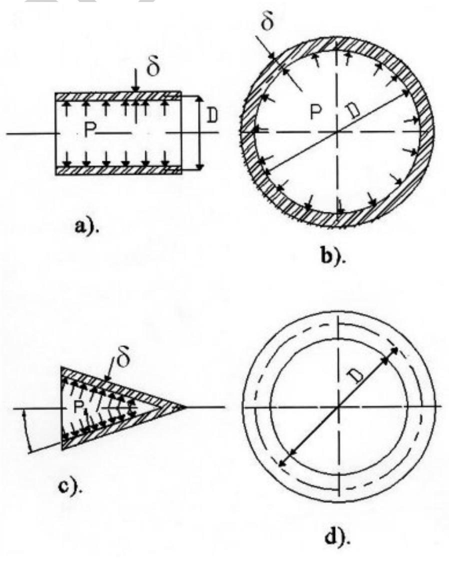

Figure 1. Basic types of shells and their load schemes: a – cylindrical, b – spherical, c – conical, d – toroidal; p – pressure (internal or external), D – mean diameter, δ – wall

thickness, α – conical shell angle, D_T – tore mean diameter

Real pressure vessels are usually combinations of cylindrical, spherical, conic and toroidal shells and types of their combinations as well as with covers, bottoms, flanges and plugs.

According to classification of chemical technologies all apparatuses can be conditionally categorized in four following types.

Tanks (reservoirs) for collection, storage and distribution of liquid and gaseous products under hydrostatic or high pressure; separation of liquid and gaseous phases of operating mediums under the action of applied gravity, inertia forces or as a result of filtration on mesh and other porous materials; or for pressure treatment of placed inside products or items (see Figure 2). Inside the high pressure tanks various auxiliary constructive elements – piping, breaking walls (screens), separation units, swirl vanes, diffusers and converging tubes, filtering mesh packages and perforated sleeves, plates with dump packing, barriers, cradles, etc. can be mounted.

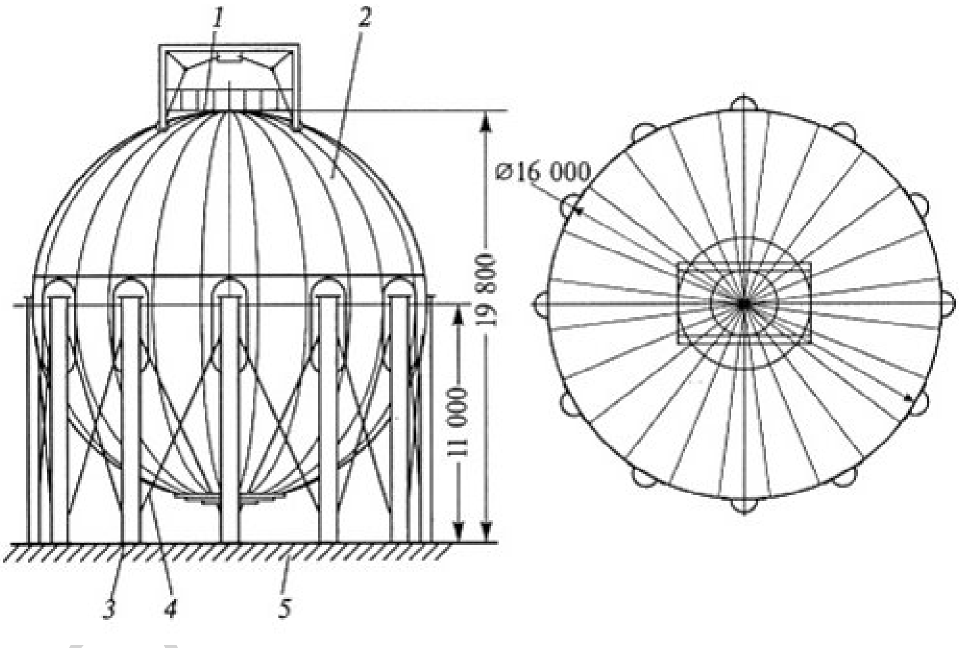

Figure 2. Scheme of the ball-type tank 2000 m^3 capacity: 1 – operating floor, 2 – shell, 3 – leg member, 4 – brace, 5 – ring-type continuous footing

Heat exchangers are designed for heating, cooling and condensing of different working media as well as for use in chemical processes. High pressure heat exchangers usually present shell-and-tube apparatuses with direct (see Figure 3) or U-shaped tubes. The heat exchangers of coil, "tube-in-tube" type, etc. are also in use.

Columns (towers) – mass exchange apparatuses in which one or several components of initial product mixture are transferred from one phase into another, i.e. absorption, rectification, extraction, adsorption, dissolving and drying processes are carried out.

High pressure columns or towers are the vertical installations inside of which bodies like the packing support, mass exchange plates and various design packing are installed.

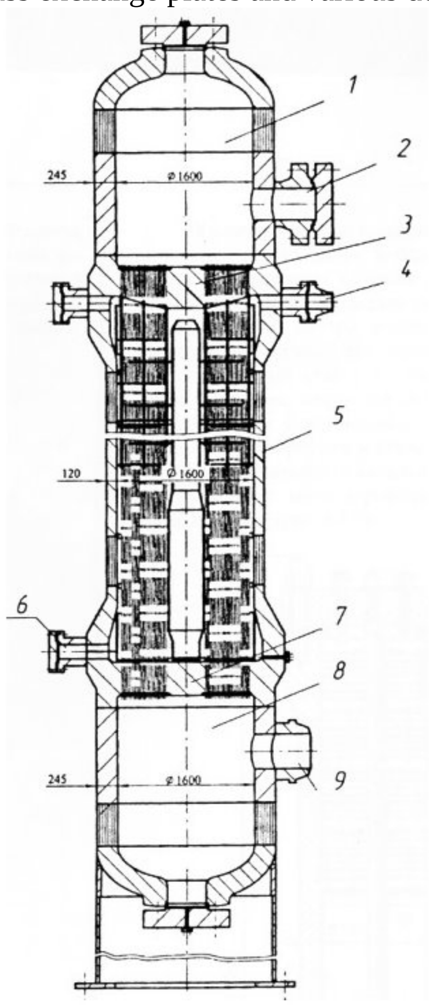

Figure 3. High pressure heat-exchanger (inside tubes – hydrogenous gas, parameters: p=32 MPa, T=350^{o}C, tube space – water, parameters: p=13 MPa, T= 330^{o}C): 1 – tube space upper chamber; 2 – gas inlet; 3 – upper tube plate; 4 – water outlet; 5 – tube space housing; 6 – water inlet ; 7 – bottom tube plate; 8 – tube space bottom chamber; 9 – gas outlet

In majority of cases the protection sleeve fabricated from corrosion resistant material with outside heat insulation coating to protect the body from corrosion damage and overheat is used. To improve the protection efficiency the gap between the body and such sleeve is filled with neutral cold working medium that later is transferred into the reaction space of the column (see Figure 4).

Reactors and autoclaves are designed to perform physical and chemical processes including those using catalytic agents. These are vertical installations with various packing, racks and buckets for catalysts, blending units, reaction media delivery systems and other modules mounted inside. In Figure 5 the multilayer autoclave for hydrothermal synthesis of crystals under a pressure of 70MPa is presented. The apparatuses operating under pressure greater than 100MPa are used at high pressure polyethylene production (see Figure 6).

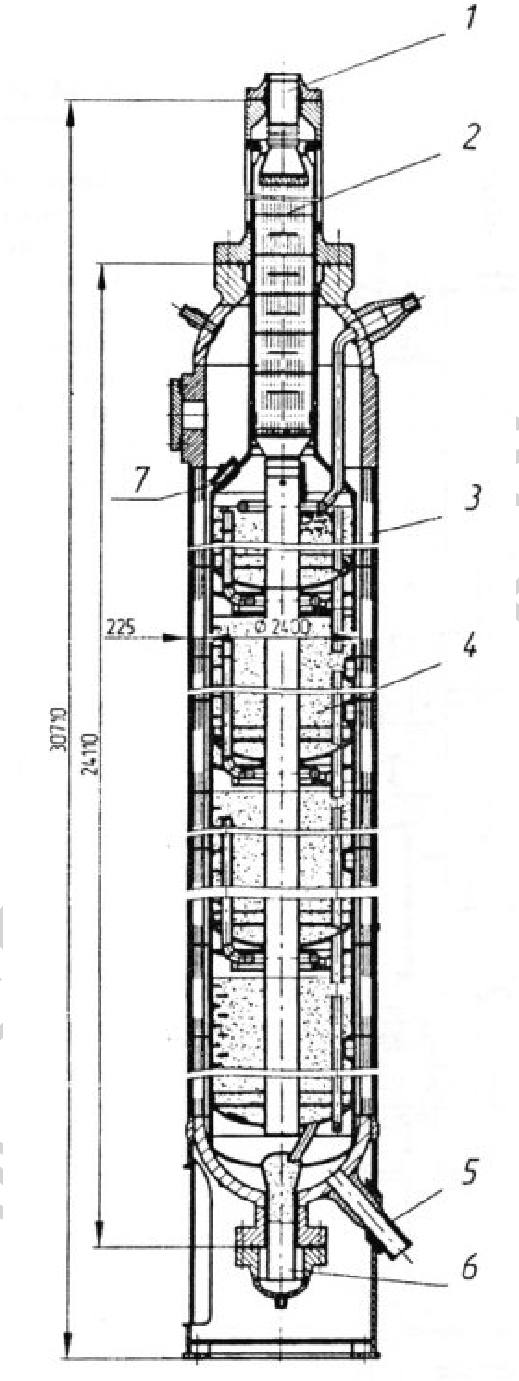

Figure 4. Ammonia synthesis tower (p=32MPa, T=300^{o} C): 1 – gas inlet, 2 – heat-exchanger, 3 – housing, 4 – catalysts box, 5 – gas outlet, 6 – on-tube catalyst dischargers, 7 – catalyst load hatch

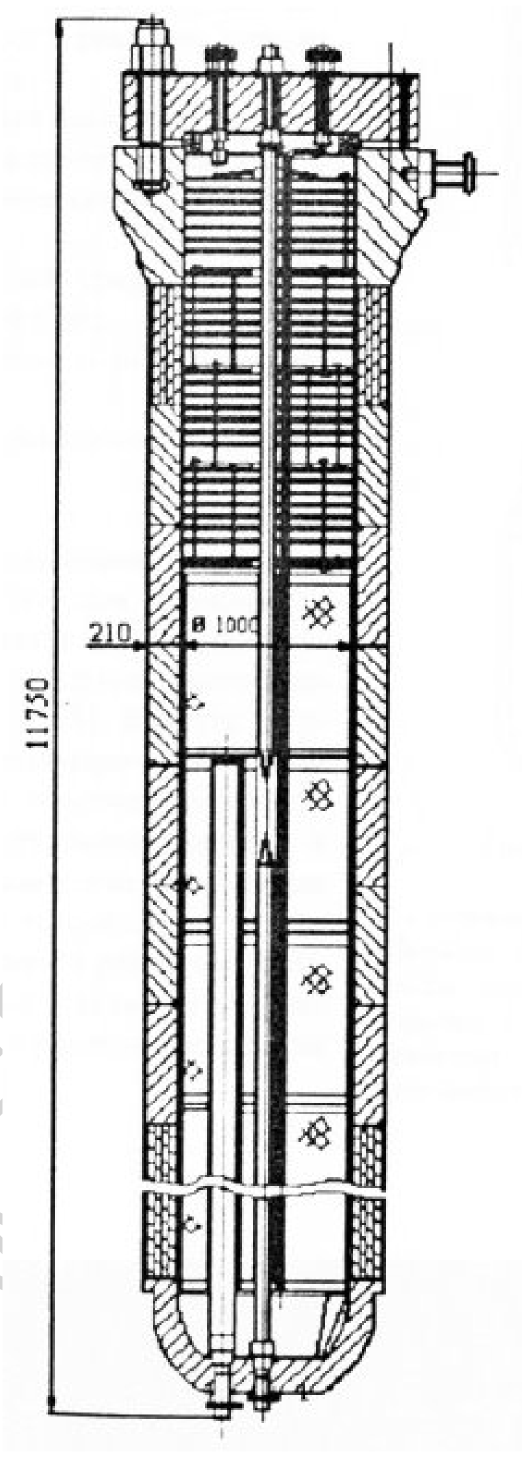

Figure 5. Autoclave for hydrothermal crystals synthesis (p=70MPa, T=400^{o} C)

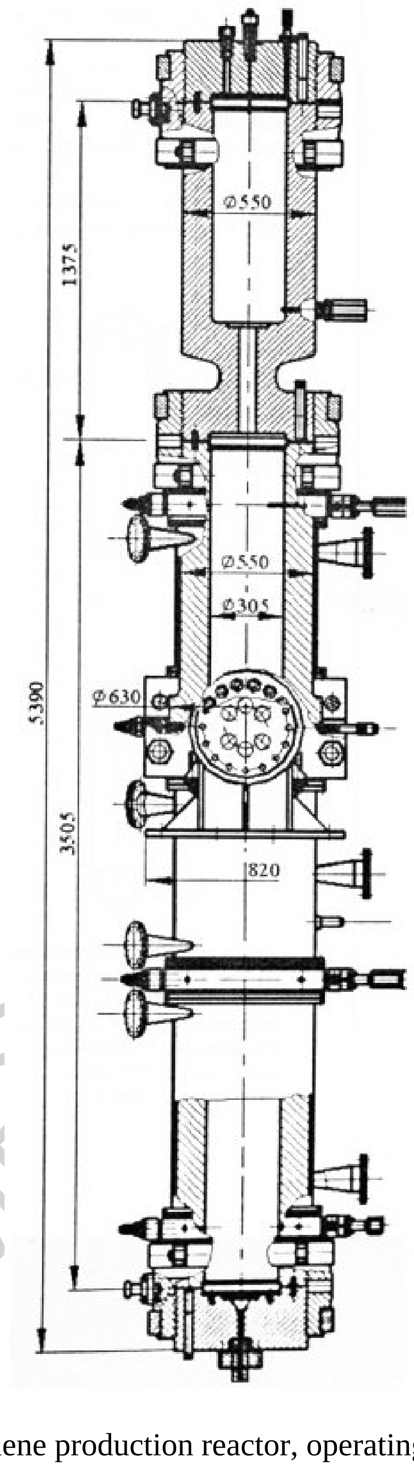

Figure 6. Polyethylene production reactor, operating pressure 144 MPa

According to function the pipelines are classified as main pipelines and industrial ones.

In metallurgy widely used are furnace pressure chambers, open-hearth furnaces, converters and some other types of equipment.

In thermal power industry various types of steam boilers and turbine casings are used as structural components.

No doubt one of the most critical elements of Nuclear Power Plant (NPP) structure with reactor operating on thermal or fast neutrons is the reactor' vessel exposed to great thermal and mechanical loads (temperature – 20…350^{o}C, pressure – 0…250MPa), radiation flow (high energy neutrons > 0.5MeV and integral fluence > 10^{18}neutrons/cm^{2}) and corrosion active media (air, water, high grade water, steam-water mixture, steam, liquid metal– sodium (Na), bismuth (Bi), lead (Pb)).

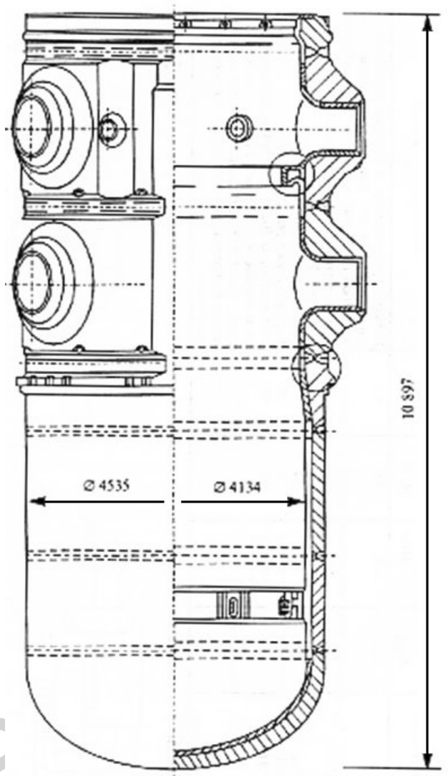

Figure 7. WWER-1000 reactor casing

In Figure 7 presented is the design of water moderated reactor vessel of WWER-1000 type. The elements of steam generators are subject to severe operating conditions as well. Beside the modules mounted inside the vessel and exposed to direct radiation causing the steel embrittlement, the metal of the reactor vessel of WWER type and technological channels of the reactor of RBMK type are also affected by direct radiation. The corrosion conditions for the most NPP structures are determined by specially decontaminated water presence while steam generators, separator bowls and pressurizers typically are under influence of steam-water mixture. In steam supply lines the steam is the main medium working component. During their service life (approximately 30—40 years) pressure vessels and piping are exposed to cyclic thermal and mechanical loads (above 100…1000 cycles), this causes fatigue damages of metal and possibility of origination of fatigue, corrosion-fatigue cracks in zones of stress concentration and presence of metal discontinuity.

To fabricate the reactor vessel seamless rolled shells with no longitudinal joints are used. The pressure vessel shells (sidewalls) are rolled and have longitudinal joints while pressure vessel bottoms are stamped.

Specific group of pressure vessels are nuclear reactor protection jackets, i.e. containments and confinements.

Design elements of the thermonuclear installations TOKAMAK are toroidal shells. The specific feature of large TOKAMAKs, as mechanical systems, is the presences of significant ponder motive loads acting in combination with specific operating conditions. In TOKAMAKs the forces of hundred thousand tones arise, leading to large mechanical stresses in the installation elements.

Structures with body of round shape: cylinders, tubes, hulls of deep-diving vehicles, etc. are widely used in the shipbuilding industry. As deep water apparatuses the submarines (SM) able to move and maneuver both on sea and sub sea (in preset diving depth range) can be mentioned. The lower limit of sub sea operation is determined by the structure strength that sets limits, when in sub sea position, on the internal atmosphere volume that, in its turn, is characterized by hydrostatic pressure less than the external pressure; this volume is outboard water tight. Such structures are called rigid or robust. They are designed to be exposed to outside pressure equal to $k_s \rho g H_{\lim}$, where $H_{\lim}$ — limiting (maximal allowable) SM diving depth; ρ — outside water density; g — gravitational acceleration; k_s — safety factor ($k_s = 1,3...1,8$).

The basic element providing structure's strength and toughness is robust SM hull. Most of equipment and SM crew are located inside it. The robust hull is usually built of a number of matched and articulated circular cylindrical and conical shells placed horizontally relative to each other and supported by ring frames (transverse rings) plugged at the ends with strong nose and stem partition walls. Such designs make it possible to minimize the weight and achieve acceptable shape of SM to place the equipment inside. In Figure 8 the standard design of diesel-electrical SM is presented. The dot-and-dash line marks the envelope of "lightweight" (outside) hull structurally connected with the SM.

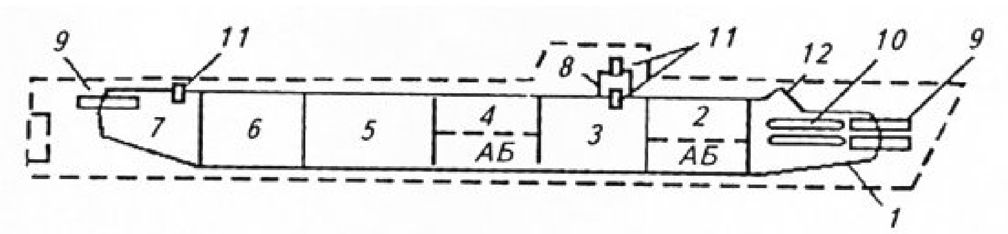

Figure 8. Scheme of rigid hull (RH) compartments of the diesel-electrical submarine (SM): 1 – nose torpedo compartment, 2 – nose battery compartment and man-tended module, 3 – central control post of SM, 4 – stem battery compartment and man-tended module, 5 – diesel-fuel compartment, 6 – electromotor compartment, 7 – stem torpedo compartment, 8 – robust cab, 9 – torpedo apparatus, 10 – spare torpedoes, 11 – access hatches, 12 – torpedoes loading hatch, AB – battery

Based on design the SM hulls can be classified into the three following groups: single hull, tripartite and double hulls (see Figure 9, a to d). The single hull SMs are lightweight hull free. The tripartite SMs do have light hull that covers SM with deck-structure from the top but not along its perimeter (i.e. the lower part of the SM is opened). One of the tripartite SM modifications is the tripartite SM with attachments that do not connect in their upper part with the deck-structure). Double hull SMs do have light weight hull that covers the SM along its perimeter together with the deck-structure.

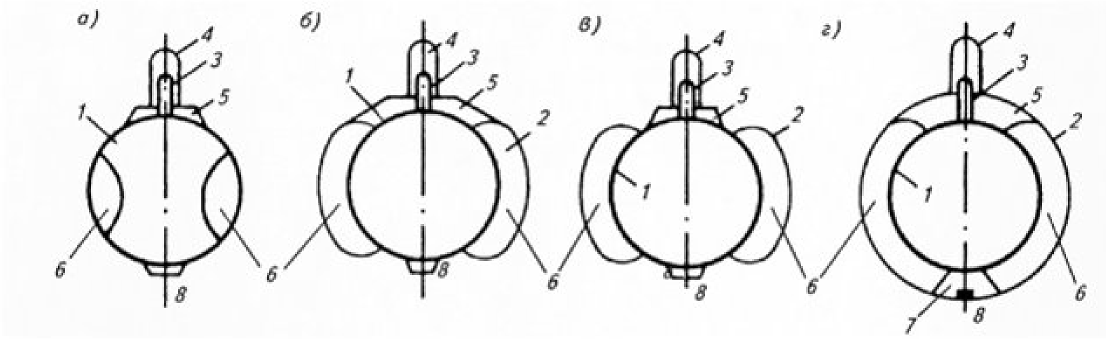

Figure 9. Design types of submarines (SM) (cross-sections): a – single-hull, b – tripartite hull, c – tripartite hull with bulls, d – double hull; 1 – rigid hull, 2 – lightweight hull, 3 – robust cab, 4 – superstructure, 5 – building-up, 6 – driving ballast tank or board space fuel tanks, 7 – penetrable enclosures, 8 – docking keel

Fuselage is one of the most critical elements of aircraft structures providing connection of different parts in an aircraft. For example, from the load-carrying ability point of view the aircraft fuselage serves as interlinking part for other separate components; it serves as base the support for wings, empennage, chassis, propulsion system, etc.

The most developed and widely used form of reinforced shell is one that consists of longitudinal reinforcements (stringers, beams), transverse reinforcements (transverse frames) and thin outer sheathing. The shape of reinforced fuselage shell along most of its length is cylindrical with circular or oval transverse cross-section and conical fore body and sternpost edges. Depending on the aircraft purpose the typical shell design can have various construction features, for example, framed cut-outs (windows, doors, chassis niches, etc.) and partitions (floors, pressure dome).

In the points of wings and empennage fixing to fuselage various sophisticated designs are used. The basic components are typically fixed to fuselage by means of powerful reinforcing transverse frames which can take significant loads occurring in the other aircraft parts and transfer them to fuselage structure. The fuselages of modern fighter planes have especially sophisticated reinforcement design schemes. These are integral structures consisting of sets of beams, plates, shells connected in one comprehensive three-dimensional system.

To perform scientific research on events and processes of aircraft streamline flow as well as to determine the aerodynamic load and its distribution along plane parts the planes and aircrafts prototypes are tested inside a wind tunnel. A wind tunnel itself is a complex engineering structure with such basic elements as jets, subsonic and supersonic diffusers, ejectors, working parts, throttles and other contour elements used in simulating installations and test benches. The scheme of a wind tunnel is presented in

Figure 10. The uniform gas flow with variable, adjustable parameters (flow rate, pressure, temperature, density, low turbulence level and low level of acoustic disturbances) is generated in the tunnel. The aircraft prototype with geometry similar to one of the original object is placed inside the flow; by means of supporting unit and special mechanisms the prototype is rotated relative to three coordinate axes. The speeding up of gas preliminary stagnant in the wind tunnel's premix chamber is provided by means of specially shaped jet nozzle. In Figure 11 the drawing of the jet-nozzle used for flow speeding up at low subsonic speed is presented.

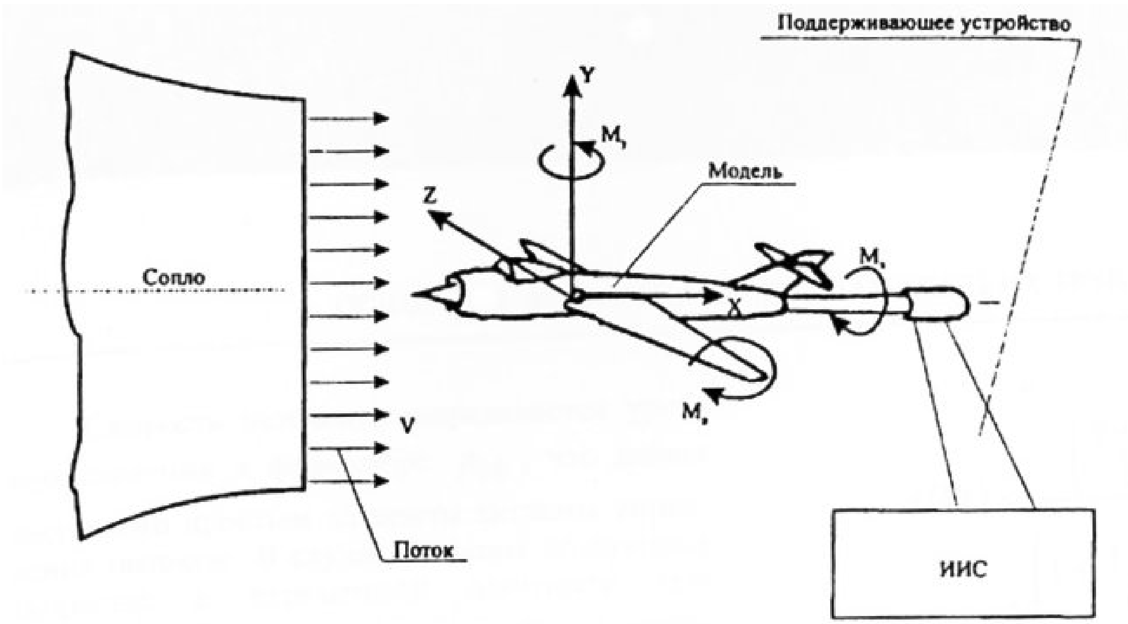

Figure 10. Wind tunnel schematic diagram

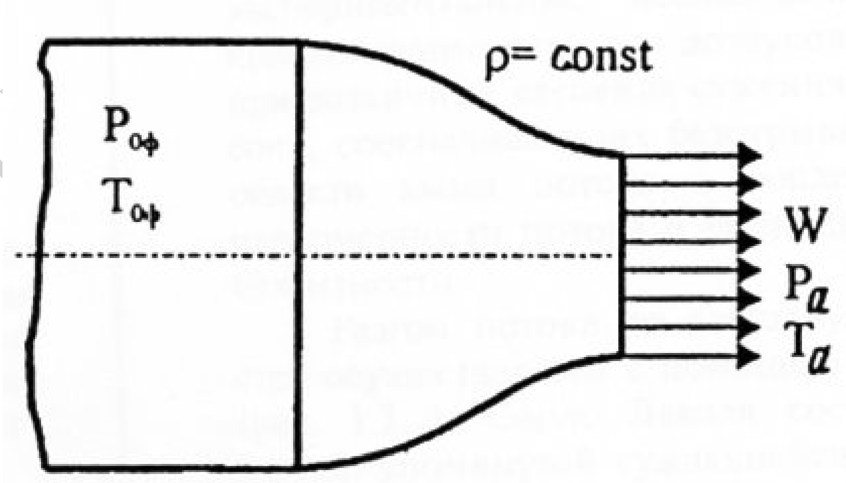

Figure 11. Scheme of speeding up jet used at low subsonic speeds

In rocket installations as well as space stations the fuel tanks and combustion chamber are examples of shell structures use.

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Biographical Sketches

N.A. MAKHUTOV was born in Bryansk Region (Russia) on September, 29th, 1937. He graduated from the Moscow Aviation Technological Institute in 1959 and was awarded Ph.D. degree in 1964, D.Sc. degree in 1973 and Associate Member of the Russian Academy of Sciences in1987. Now Professor Makhutov is head of Department of Strength, Lifetime and Safety of Engineering Structures at the Mechanical Engineering Research Institute of the Russian Academy of Sciences.

His major is mechanical engineering including mechanics, engineering safety, fracture mechanics, strength, high and low cycle fatigue, wear and friction. Professor Makhutov has worked out scientific basis of engineering safety, survivability and lifetime extension of structures in industry. The criteria of strength, lifetime extension and fracture toughness of materials were suggested for design, manufacturing and operation stages.

Professor Makhutov is Chairman of the Russian committee of the European Structural Integrity Society

(ESIS), Chairman of Scientific Council on Emergency in the Commonwealth of Independent States, the Editor-in-chief of journal "Problems of Safety at Emergency", a member of editorial boards of journals "Industrial Laboratory. Diagnostics of Materials", "Strength of Materials", "Fatigue and Fracture of Engineering Materials & Structures".

YU. G. MATVIENKO was born in Moscow (Russia) on March, 7th, 1956. He graduated from the Moscow Engineering Physical Institute in 1980 and was awarded Ph.D. degree in 1985 and D.Sc. degree in 1993. Now Professor Matvienko is head of Laboratory of Modeling Damage and Fracture at the Mechanical Engineering Research Institute of the Russian Academy of Sciences.

His major is mechanical engineering, especially, fracture mechanics, fatigue, strength, reliability, survivability and safety of engineering structures damaged by cracks and crack-like defects. Professor Matvienko has worked out scientific fundamentals and unified methods of an analysis and substantiation of survivability and engineering safety of damaged structures. Scientific interest also includes models, criteria and approaches of elastic-plastic fracture mechanics, short crack propagation, problems of safety and lifetime extension of structures in atomic power engineering, chemical and petrochemical manufactures, airspace and aviation.

Professor Matvienko is the Deputy Chairman of the Russian committee of the European Structural Integrity Society (ESIS), member of Scientific Council of the Russian Academy of Sciences on a problem "Reliability, Lifetime and Safety of Engineering Systems ", member of an editorial board of journal "Industrial Laboratory. Diagnostics of Materials". He is listed in several editions of "Who's Who in Science and Engineering".

Professor Matvienko was invited in University of Sheffield (England) in 1994-1995 as a visiting scientist and in Korea Atomic Energy Research Institute (South Korea) in 1998-1999 and 2003-2005 as an invited expert.