Zbigniew Mirski, Kazimierz Banyś, Zbigniew Fałek, Tomasz Piwowarczyk

FEM-aided Design of Welded Pressure Vessels According to ASME BPVC Regulations

Abstract: The article presents the historical background and a brief introduction to the American ASME BPVC regulations concerned with welded boilers, pressure vessels and nuclear facilities. The article presents a methodology for the design of two-shell tube welded pressure vessel (autoclave) based on ASME Sec. VIII Div. 1 regulations. Due to the lack of a computational method (calculation based on formulas) for the complete pressure vessel according to ASME Sec. VIII, Div. 1, related calculations were performed using a computational method according to ASME Sec. VIII, Div. 2 Part 5. The results of the calculations are presented in the form of tables, graphs and numerically generated visualisation.

Keywords: ASME regulations, welded boilers, pressure vessels, nuclear facilities

Introduction

Boilers and pressure vessels are used worldwide in various industries. They are naturally present in the power engineering and gas engineering sectors. In order to ensure the safety and operational efficiency of these vessels, necessary legal regulations have been developed. These regulations constitute the basis for design and manufacture as well as conformity-oriented independent inspection and certification. Such activities contribute to the constant growth in the importance and popularity of regulations developed and published by the American Society of Mechanical Engineers (ASME) as internationally-recognised regulations.

ASME is the New York-seated American Society of specialists in Mechanical Engineering. The organisation was founded in 1880 in response to numerous failures of steam boilers increasingly commonly used in various industries [3]. Presently the organisation has over 130,000 members in 158 countries of the world [1].

On the basis of ASME regulations in 1907 in the state of Massachusetts, the first legal regulations related to the design and manufacture of steam boilers were developed. The move was preceded by public outrage following a number of boiler explosions which had taken place in the state with the most tragic accident being the boiler explosion of 20 March 1905 in a Grover shoe factory in Brockton which claimed 58 lives leaving 150 wounded [11].

In 1911, the ASME established the Pressure Vessel Code Committee which developed principles for designing stationary vessels with defining the values of permissible pressure. The code was issued in 1914 and published in the following year [13].

prof. dr. hab. inż. Zbigniew Mirski (Professor PhD, hab. Eng.), dr inż. Tomasz Piwowarczyk (PhD Eng.) – Wrocław University of Technology, Department of Materials Science, Welding and Strength of Materials;
prof. dr inż. Kazimierz Banyś (Professor PhD (DSc) Eng.) – Research and Implementation Company, Wrocław ;
mgr inż. Zbigniew Fałek (MSc Eng.) - Research and Design Bureau "MIFA-Projekt", Oława, Poland

Presently, the Association publishes globally recognised regulations concerning the design, manufacture and inspection of boilers, pressure vessels and nuclear facility elements - ASME Boiler and Pressure Vessel Code (ASME BPVC). Engineers and experts representing manufacturers, inspection authorities and users work on a voluntary basis in commissions dealing with the development, update and introduction of changes in subsequent revisions of such regulations.

Revision of ASME BPVC regulations

The set of ASME BPVC regulations contains 12 sections [2]:

– sections I, III, IV, VIII, X and XII are concerned with structural requirements being the basis for equipment certification,
– sections II, V and IX related to structural regulations,
– sections VI, VII and XI contain operational regulations valid once devices have been commissioned at the users' premises.

Structural regulations:

- ASME BPVC Section I - Rules for Construction of Power Boilers,
- ASME BPVC Section III - Rules for Construction of Nuclear Facility Components – Div. 1, 2, 3, 4 and 5,
- ASME BPVC Section IV - Rules for Construction of Heating Boilers,
- ASME BPVC Section VIII - Rules for Construction of Pressure Vessels – Div. 1, 2 and 3,
- ASME BPVC Section X - Fibre-Reinforced Plastic Pressure Vessels,
- ASME BPVC Section XII - Rules for the Construction & Continued Service of Transport Tanks.

Regulations related to structural regulations:

- ASME BPVC Section II - Materials – Part A, B, C and D,
- ASME BPVC Section V – Non-destructive Examination,
- ASME BPVC Section IX - Welding and Brazing Qualifications.

Regulations related to the operation of boilers and pressure vessels:

- ASME BPVC Section VI - Recommended Rules for the Care and Operation of Heating Boilers,
- ASME BPVC Section VII - Recommended Guidelines for the Care of Power Boilers,
- ASME BPVC Section XI - Rules for In-service Inspection of Nuclear Power Plant Components.

Compatibility of ASME BPVC Regulations with PED Directive

Directive 97/23/WE of the European Parliament and of the Council od 29 May 1997 on the approximation of the laws of the Member States concerning pressure equipment (PED) has established the criteria which have to be satisfied by manufacturers in order to ensure free trade in produced pressure vessels throughout all EU member states. The application of the ASME BPVC regulations is also possible for pressure vessels requiring certification for CE marking. The basic condition is the satisfaction of additional requirements arising from the difference in requirements between PED and ASME BPVC. Also, the necessity of fulfilling PED requirements by American producers stimulates ASME to implement changes harmonising the ASME BPVC regulations with the EU requirements. Such a trend is confirmed by changes introduced in 2007 in relation to ASME BPVC Sec. VIII, Div. 2 vessel regulations making them similar in their structure to EN 13445 – Unfired pressure vessels [12].

Design and Calculations for Welded Pressure Vessels According to the ASME BPVC Regulations

Pressure vessels at design and calculation stages are dealt with by the ASME BPVC Sec. VIII Div. 1, 2 and 3 regulations. The common regulations of these divisions cover mandatory requirements, orders and guidelines for materials, design, production, inspection, testing, marking, reporting, protection against overpressure increase and certification [6-8]. In addition, Div. 1 [6] also includes requirements based on the traditional approach to design (formula-based calculations) in relation to pressure in excess of 15 pounds/inch² (0.1 MPa). Detailed requirements apply to specific types of materials used for pressure vessels structures as well as to method of their manufacture, such as welding, brazing and forging.

Pressure vessels can be fired or unfired. Pressure can come from external sources, using indirect heating or from a direct source, coming from a reaction process or from any combination of the two. Regulations contained in Div. 2 [7] can be used as an alternative to the minimum requirements specified in Div. 1. However, the principles contained in Div. 2 are more demanding than those of Div. 1 with reference to materials, structures and non-destructive testing, yet they allow higher stress values. Div. 2, in addition to the traditional approach to design, also admits calculations based on the Finite Element Method (FEM) in relation to pressure in excess of 15 pounds/inch² (0.1 MPa). The requirements provided in Div. 3 [8] apply to vessels operating under internal or external pressure in excess of 10 000 pounds/inch² (69 MPa). Div. 3 does not set any minimum or maximum pressure limits either for Div. 1 or for Div. 2 [11].

Procedure

The design procedure was performed according to the publication [9]. The subject of the design is a welded two-shell tube pressure vessel (autoclave). The vessel is intended to act as the shell of a vacuum furnace for thermal and thermo-chemical processing with high-pressure gas cooling.

Furnaces of this type are used in vacuum processes such as annealing, hardening, brazing, sintering, carburising, nitriding and in other specialist technological processes. The use of the vacuum technique enables obtaining optimum process parameters, and during thermo-chemical treatment, a clean and tarnish-free surface with edge zones free from oxides.

The design assumptions of the vacuum furnace according to the customer's requirements were the following:

- hearth load capacity – 3 Mg,
- charge dimensions (max length × height × width) – 1200×800×800 mm,
- cooling atmosphere pressure – 10 bars,
- cooling medium pressure: inner shell tube – 1.5 bar,
- maximum temperature of vessel elements under pressure – 250°C.

The design of the pressure vessel was developed on the basis of the regulations ASME BPVC Sec. II, Part D [4] and Sec. VIII, Div. 1, Part UG and Part UW [6], according to Sec. VIII, Div. 1, Example Problem Manual 1PTB-4-2012 [7].

Design Assumptions and Boundary Conditions for Calculations

Design assumptions and calculations constitute an important part of the pressure vessel design process. The correctness of design assumptions and calculations affects many factors, the most important of which is the operational safety of the structure. The selection of proper computational methods also determines the manufacturing technological possibilities, which directly translates to the economic aspect.

Due to the lack of a computational method based on the traditional approach to the design of a complete pressure vessel according to Sec. VIII, Div. 1, by Authorised Inspector's (AI) acceptance on the basis of the regulations contained in Sec. VIII Div. 1, Introduction U-2 (g), numerical calculations according to Sec. VIII, Div. 2 Part 5 were conducted. In order to ensure the same structural safety level as in the case of calculations consistent with Sec. VIII, Div. 1, the following assumptions were adopted [7]:

- permissible stresses consistent with Sec. VIII, Div. 1, UG-23,

Table 1. Properties of steels used at an operating temperature of 250°C

No.	Name of element	Properties according to Sec. II Part D ed.2010 Add.2011a						
		Steel designation	S_m [MPa]	S_Y [MPa]	S_{Ya} [MPa]	S_{Ua} [MPa]	E [GPa]	ν
1	Flange	SA-105	134	250.0	204.0	483.0	189.0	0.30
2	Bottom and shell tube	SA-516M GR485	138	260.0	216.0	483.0	189.0	0.30
3	Nozzle branch	SA-106 GR.B	128	240.0	198.0	414.0	189.0	0.30
4	Nozzle branches made of rods	SA-675M Gr485	132	240.0	198.0	483.0	189.0	0.30

S_m – permissible stresses,
S_Y – yield point,
S_{Ya} – yield point at the room temperature,
S_{Ua} – tensile strength at the room temperature,
E – module of elongation elasticity - IID Table TM-1,
ν – Poisson ratio - IID Table PRD.

- welded joint coefficients consistent with Sec. VIII, Div. 1, UW-11 and UW-12,
- boundary computational stresses consistent with Sec. VIII, Div. 2, Part 5.2.2,
- vessel corrosive wear - 1 mm during active life (approximately 25 years).

The analysis was carried out for the linear-elastic material range on the basis of Sec. VIII, Div. 2, Part 5.2.2 – for the calculations of strength in the test run. The condition of final calculations was that the stresses of vessel pressure elements and of welded joints demonstrated on the basis of numerical calculations should be lower than the boundary stresses contained in Sec. VIII, Div. 2, Fig. 5.1.

Properties and Chemical Composition of Materials Used

The properties of materials were adopted in accordance with Sec. VIII Div. 1 UG-4 and meeting the conditions defined for linear-elastic materials. Table 1 contains the mechanical properties of steels used for pressure elements, at an operating temperature of 250°C, in accordance with Sec. II Part D (Metric) [5]. The chemical composition of selected steels is presented in Tables 2-4 [4]. The chemical composition is selected by the manufacturer in a way enabling the obtainment of the desirable mechanical properties of steel at the operating temperature. The metallurgical weldability of steel is determined by calculating the carbon equivalent:

$$Ce = \%C + \%Mn/6 + (\%Cr+\%Mo+\%V)/5 + (\%Ni+\%Cu)/15.$$

Table 2. Chemical composition of the SA 105 steel for forgings of unalloyed steel in% by weight.

C	Mn	P	S	Si	Cu	Ni
≤ 0.35	0.6-1.05	≤ 0.035	≤ 0.04	0.10-0.35	0.40	0.40
Cr	**Mo**	**V**	**Nb**	**Cu+Ni+Cr+Mo**	**Cr+Mo**	**Fe**
0.30	0.12	0.05	0.02	≤1 .00	≤ 0.32	rest

Carbon equivalent Ce = 0.57%. Steel applications: pipe elements (flanges, connectors and valves) in pressure systems.

Table 3. Chemical composition of the SA-516M GR485 unalloyed steel in% by weight

Sheet thickness [mm]	C	Mn	P	S	Si	Fe
t ≤ 12.5	0.27	0.85-1.20	0.035	0.035	0.15-0.40	rest
12.5 ≤ t ≤ 50	0.28	0.85-1.20	0.035	0.035	0.15-0.40	rest

Carbon equivalent Ce = 0.41%. Steel applications: welded pressure vessels of higher toughness.

Table 4. Chemical composition of the SA-106 GR.B unalloyed steel in% by weight

C	Mn	P	S	Si	Cu
0.30	0.29-1.06	≤ 0.035	≤ 0.035	≥ 0.10	≥ 0.40
Ni	**Cr**	**Mo**	**V**	**Cu+Ni+Cr+Mo+V**	**Fe**
≤ 0.40	≤ 0.40	≤ 0.40	≤ 0.08	≤ 1.0	rest

Application: seamless steel pipes of higher toughness for operation at higher temperatures.

The data related to the chemical composition of steel in% by weight are provided on the basis of a material certificate. The SA-675M Gr485 steel contains, among others, in% by weight, below 0.20% Cu with the amount of impurities being maximum 0.04% P and 0.05% S. Application: special quality hot-forged steel rods for pressure vessel nozzle branches.

Table 5. Values of boundary stresses for the steels used

No.	Name	T [°C]	Steel	Values of boundary stresses according to Sec. VIII, Div. 2, Figure 5.1		
				P_m [MPa]	P_L [MPa]	$P_L + P_b$ [MPa]
1	Flanges	250	SA-105	134.0	201.0	201.0
2	Bottom and shell tube	250	SA-516M GR485	138.0	207.0	207.0
3	Nozzle branches	250	SA-106 GR.B	128.0	192.0	192.0
4	Nozzle branches made of rods	250	SA-675M Gr485	132.0	198.0	198.0

P_m – total pressure stresses, $P_m = S_m$, P_L – local pressure stresses, ^{PL} =1.5 S_m, P_b – bending stresses, $P_L + P_b = 1.5\ S_m$.

Table 6. Welded materials, welding consumables and methods used [10]

Weld no.	Weld thick-ness	Parent metals	Joint coefficient	Welding method/consumables			heating time [min]	Max interpass temperature [°C]
				Penetration	Filling and face	Pre-welding		
A1, B1, C1	18	SA 516 Gr. 485 SA 516 Gr. 485	0.85	SAW/UP F7A8-EM12K	SAW/UP F7A8-EM12K	SAW/UP F7A8-EM12K	10	200
A2, B2	6	SA 516 Gr. 485 SA 516 Gr. 485	0.85	GMAW/MAG ER70S6	GMAW/MAG ER70S6	-	10	200
A3, B3	16	SA 516 Gr. 485 SA 516 Gr. 485	0.85	GMAW/MAG ER70S6	GMAW/MAG ER70S6	GMAW/MAG ER70S6	10	200
B4	-	SA 105 SA 106 Gr. B	0.85	GTAW/TIG ER70S6	GTAW/TIG ER70S6	-	10	200
C2	6	SA 516 Gr. 485 SA 516 Gr. 485	NA	-	SAW/UP F7A8-EM12K	-	10	200
C3	16	SA 516 Gr. 485 SA 516 Gr. 485	NA	GMAW/MAG ER70S6	GMAW/MAG ER70S6	GMAW/MAG ER70S6	10	200
D1	-	SA 516 Gr. 485/ SA 106 Gr. B SA 675 Gr. 485	NA	GTAW/TIG ER70S6	SMAW-E E7018	-	10	200
D2	-	SA 516 Gr. 485/ SA 106 Gr. B SA 675 Gr. 485	NA	GTAW/TIG ER70S6	SMAW-E E7018	-	10	200
D2.1	-	SA 516 Gr. 485 SA 106 Gr. B	NA	GTAW/TIG ER70S6	SMAW-E E7018	-	10	200
D3	-	SA 516 Gr. 485 SA 106 Gr. B	NA	GTAW/TIG ER70S6	SMAW-E E7018	-	10	200
D4	-	SA 516 Gr. 485 SA 106 Gr. B	NA	GTAW/TIG ER70S6	SMAW-E E7018	-	10	200
E1	a≥ 0.7t	SA 516 Gr. 485 SA 516 Gr. 485	NA	-	GMAW/MAG ER70S6	-	10	200
E2	-	SA 516 Gr. 485 SA 516 Gr. 485	NA	GMAW/MAG ER70S6	GMAW/MAG ER70S6	GMAW/MAG ER70S6	10	200

Boundary Conditions for Vessel Strength-related Calculations

Stresses were adopted in accordance with Sec. VIII Div. 1 UG-22:

- gravitational acceleration gz = 9.81m/s2,
- transformer weight mT = 1200 kg,
- weight of the heating chamber with a charge mGW = 5000 kg,
- weight of the fan mW = 1700 kg,
- moment triggered by the fan operation in the OX-axis MOX = 800 Nm,
- moment triggered by the fan operation in the OZ-axis MOZ = 13 600 Nm,
- maximum temperature of the pressure vessel elements in operation - T = 250°C,
- internal computational pressure p = 10 bars,
- coolant overpressure pn = 2.5 bars.

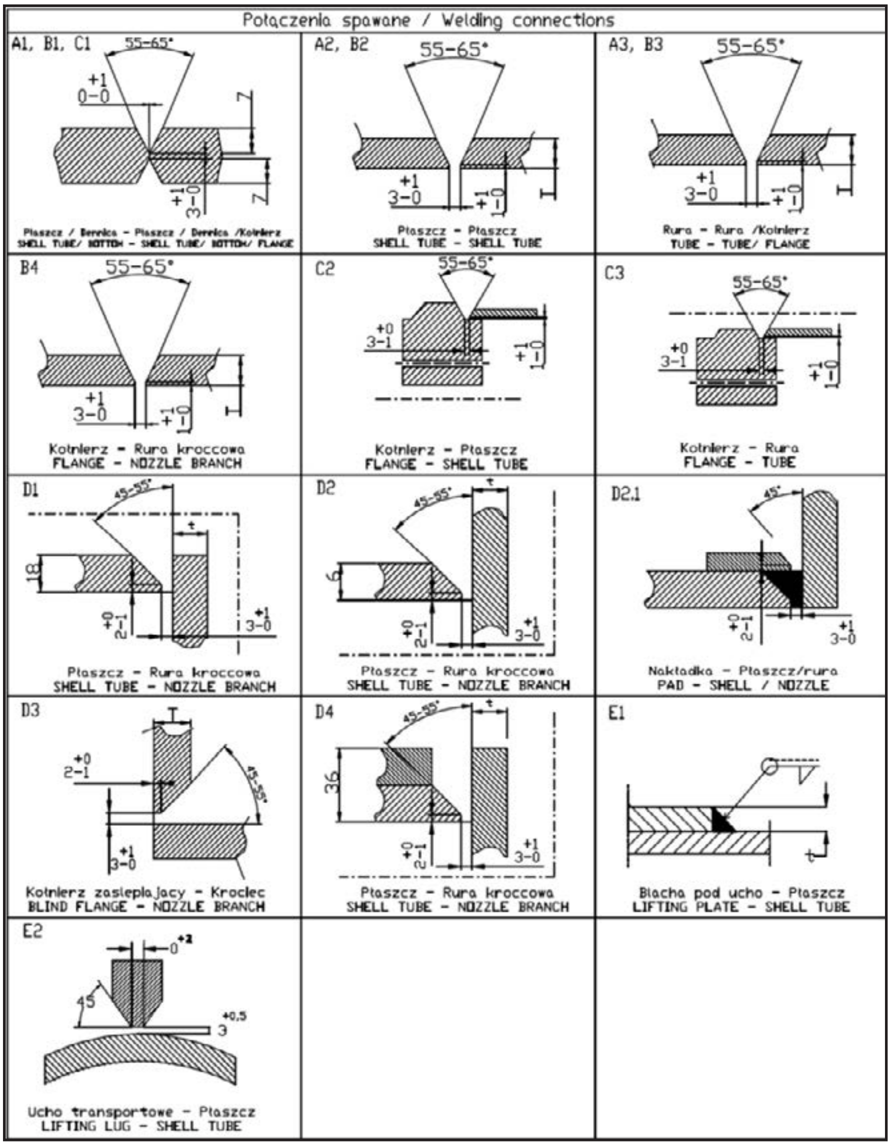

Fig. 1. Preparation of element edges for welded joints specified in the vessel design along with dimensions [6]

Fig. 2. Pressure vessel model (without simplified representations) for numerical calculations

The material mathematical model adopted was linear-elastic according to Sec. VIII Div. 2 Part 5.2.2. The permissible boundary stresses were determined according to Sec. VIII Div. 2, Fig. 5.1. The values of the boundary stresses for the materials used are presented in Table 5.

Welded joints

The structural solutions of the welded joints of the pressure vessel individual elements were developed on the basis of Sec. VIII, Div. 1, UW- 11 and UW-12. The joints are presented in Figure 1. The data for Figure 1 - workpieces, welding consumables and welding methods are presented in Table 6. The information provided refers to pre-weld preheating time according to AWS guidelines, but obviously it refers to preheating to a previously specified temperature.

Reduced Stresses of Welded Joints according to the von Mises Hypothesis

The pressure vessel model for numerical calculations (Fig. 2) was designed using INVENTOR 2013 software. The numerical calculations and distribution of stresses were generated using ANSYS 13 software (Fig. 3, 4 and 6). On the basis of the results obtained, the diagrams of welded joint stress

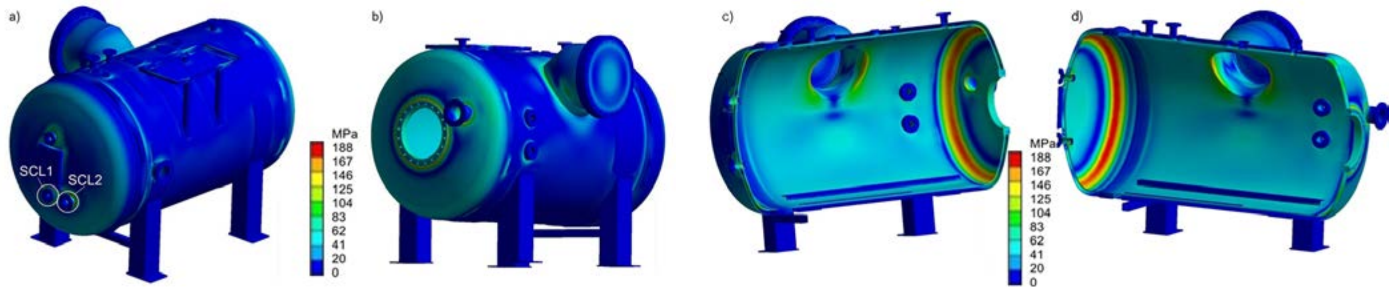

Fig. 3. Distribution of reduced stresses according to the von Mises hypothesis in the pressure vessel designed: front view (a) and rear view (b) and cross-sectional views (c and d)

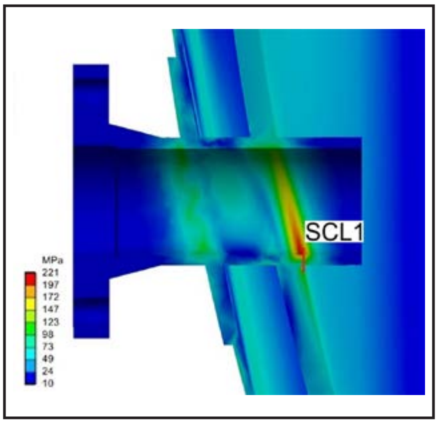

Fig. 4. Location of stresses in the SCL1 zone (see area in Fig. 3a)

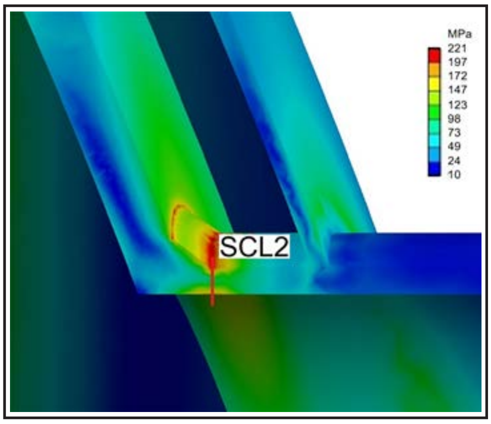

Fig. 6. Location of stresses in the SCL2 zone (see area in Fig. 3a)

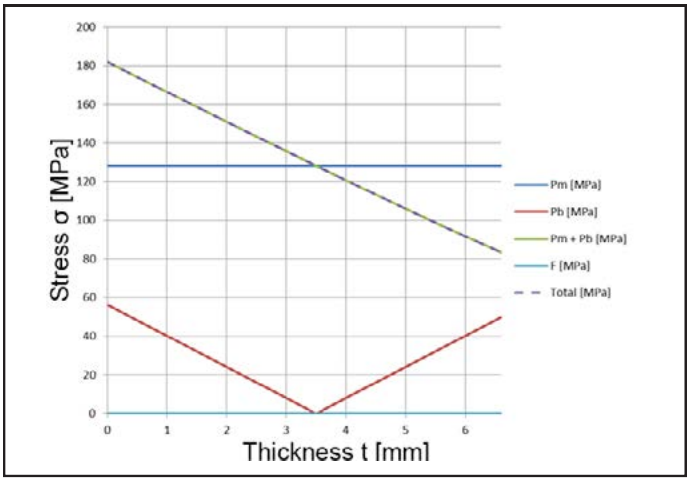

Fig. 5. Linearization of stress in the SCL1 zone (Fig. 4) in the area critical for the welded joint according to Figure 1-D1 (shell–nozzle branch joint)

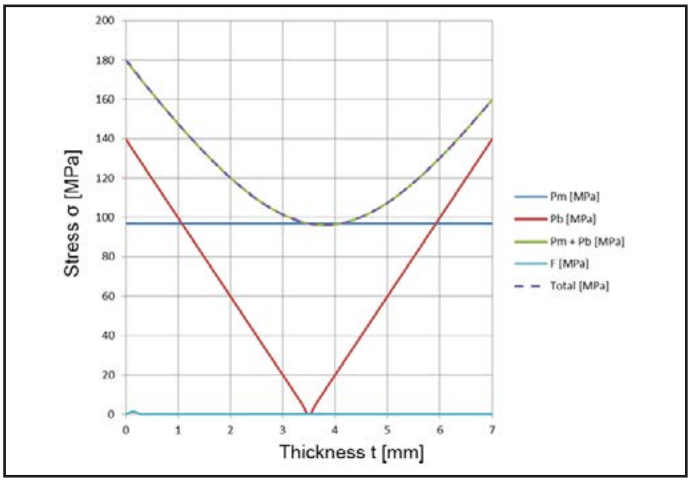

Fig. 7. Linearization of stress in the SCL2 zone (Fig. 6) in the area critical for the welded joint according to Figure 1-D1 (shell–nozzle branch joint)

Table 7. Numerical test results

No.	Name	T [°C]	Steel grade	Permissible stresses Sec. VIII div.2 Figure 5.1			Results Sec. VIII Div. 2, Part 5.2.2.		
				Pm [MPa]	PL [MPa]	PL + Pb [MPa]	Pm [MPa]	PL [MPa]	PL + Pb [MPa]
1	Flanges	250	SA-105	134.0	201.0	201.0	n/a	<70	n/a
2	Cover, bottoms and shell tube	250	SA-516M GR485	138.0	207.0	207.0	n/a	151.7	n/a
3	Nozzle branches	250	SA-106 GR.B	118.0	192.0	192.0	n/a	181.8	n/a
4	Nozzle branches made of rods	250	SA-675M Gr485	132.0	198.0	198.0	n/a	182.0	n/a

linearization were prepared (Fig. 5 and 7). The numerical calculation results are presented in Table 7. The graphic representation of results concerning the stresses in welded joints refer to selected nodes. The analysis involved the zones where critical stresses were present. Loading the vessel with the pressure of 10 bars at 250°C and with external forces caused the vessel total deformation of 1.51 mm. The relative elastic deformation was 0.097%.

Test Results – Discussion

In order to visualise the stresses present in the welded joints at selected critical points, the stress classification line (SCL) was determined according to Sec. VIII Div. 2 Annex 5.A. The linearization of stresses in the SCL zones takes into consideration the value F, i.e. the value of additional stress caused by the concentration of stresses above the level of nominal stresses resulting from operational stresses.

The thickness of the nozzle branch welded joints amounted to $t = 7$ mm. The linearization in the SCL1 cross-section (Fig. 5) reveals that the calculated stress values correspond to the values presented in Table 7. In the SCL1 cross-section the stresses deriving from the notch - value F amount to 0, which is indicated by the stress lines $P_m + P_b$ overlapping with the line of total stresses. In the SCL2 cross-section (Fig. 7) the value F is insignificant on the outer nozzle branch surface (stresses of approximately 3 MPa penetrate approximately 0.3 mm of the nozzle branch). Due to the negligible effect of such stresses it can be assumed that in the whole cross-section of the nozzle branch wall $F = 0$, as in this case the line of stresses $P_m + P_b$, also overlaps with the line of total stresses. In the remaining welded joints the linearization was ignored due to the presence of insignificant stresses ($P_m + P_b < 70$ MPa).

Conclusions

On the basis of the numerical test results (Fig. 3 and Table 7) as well as the diagrams of the linearization of welded joint stresses at critical points (Fig. 5 and 7) it was demonstrated that the results of strength-related calculations for the pressure vessel and welded joints made following the regulations of ASME BPVC Sec. VIII Div. 1 ed. 2011a and Div. 2 ed. 2011a, Part 5 meet the assumed parameters and required strength criteria.
The pressure furnace was designed and manufactured at REMIX S.A. (REMIX Joint-Stock Company) ul. Poznańska 36, 66-200 Świebodzin, Poland.

References

1. About ASME - At a Glance. ASME. Retrieved 7 November 2011.
2. An International Code - 2010 ASME Boiler & Pressure Vessel Code Section VIII Rules for Construction of Pressure Vessels - Division 1. ASME. July 1, 2011.
3. ASME. "ASME.org > About ASME". Retrieved 2011-12-27.
4. ASME BPVC Section II Part A – Ferrous Material Specifications / ed.2010 Addenda 2011a.
5. ASME BPVC Section II Part D – Properties (Metric) / ed. 2010 Addenda 2011a.
6. ASME BPVC Section VIII, Division 1, Rules for Construction of Pressure Vessels / ed. 2010 Addenda 2011a.
7. ASME Section VIII, Division 2, Alternative Rules, Rules for Construction of Pressure Vessels / ed. 2010 Addenda 2011a.
8. ASME BPVC Section VIII Division 3 - Rules for Construction of Pressure Vessels.
9. ASME BPVC Section VIII, Division 1, Example Problem Manual 1PTB-4-2012.
10. ASME BPVC Section IX, Welding and Brazing Qualifications / ed.2010 Addenda 2011a.
11. Balmer R. T.: Modern Engineering Thermodynamics. 13.10 Modern Steam Power Plants: Academic Press, 2010, p. 864.
12. Josz K.: Przepisy ASME „kluczem na nowe rynki”, Kwartalnik TÜV NORD Polska, July - September 2012, p. 4.
13. Varrasi J.: To Protect and Serve - Celebrating 125 Years Of Asme Codes & Standards. ME Magazine, June 2009.