

APPLICATION OF FKM CALCULATION ALGORITHM FOR DETERMINATION OF DEGREE OF UTILIZATION OF A MILK TANK WALL

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ARTICLE INFO	ABSTRACT
<p><i>Article history:</i> Received: November 2018 Received in the revised form: November 2018 Accepted: December 2018</p> <p><i>Key words:</i> milk, cooling tank, tank, degree of utilization, FKM Guideline, safety factor</p>	<p>The objective of the paper was to determine the level of circumferential stress in a wall of an open milk tank and to assess the tank wall degree of utilization according to the FKM Guideline calculation algorithm – Analytical Strength Assessment of Components, Made of Steel Cast Iron and Aluminium Materials in Mechanical Engineering. (German: FKM – Forschungskuratorium für Maschinenbau). The stress level in the tank wall was determined based on analytical calculations and numerical method using the FEA – Finite Elements Analysis. Numerical calculations were made in FEMAP with NX NASTRAN Solver (NASTRAN – NASA Structure Analysis). Similar stress values were found using two independent calculation methods. The difference between obtained stress values does not exceed 2%. Based on the FKM algorithm, the safety factor $j_{ges} = 1.4$ and static capacity of the tank wall $a_{sk} = 19.7\%$ were calculated.</p>

Introduction

Milk cooling time and its proper storage to the moment of collection are important factors that help to maintain high quality raw milk. Fast reduction of milk temperature has a significant impact on inhibition of the increase of an initial number of bacteria and enables longer storage time of milk with maintenance of its proper microbiological quality (Daniel, 2010; Wiercioch et al., 2010). Pursuant to directive 92/46/EEC (1992) milk after milking should be collected within two hours or cooled down to the temperature of 8°C when it is collected every day, or to the temperature of 6°C when collection is rare (Daniel, 2010; Romaniuk and Overby, 2004). According to Daniel (2010), an optimal temperature of milk storage is 4°C. Milk after milking is the most often cooled down in plate heat exchangers and then stored in cooling tanks (Jasińska et al., 2011; Romaniuk and Overby, 2004).

Requirements concerning construction of tanks for milk cooling (thermal isolation, maximum level of filling, method of founding etc.) were described in detail in the standard ISO 5708 (1983). We can distinguish silos, closed and open tanks. Open tanks are used mainly in small cowsheds with herds up to 30 pieces of dairy cows, where a stanchion-tied

stable system is used the most often (Wiercioch et al., 2010; Romaniuk and Overby, 2004). An open tank is a vertical, cylindrical tank, which has a removable cover. There is thermal isolation between the milk tank and an outer shell. Pursuant to standard ISO 5708 (1983) thermal isolation aims at limitation of the milk temperature increase so that the temperature increase does not exceed 1°C within four hours (Romaniuk and Overby, 2004). Open tanks are usually constructed as an inseparable part with a compressor unit (Daniel, 2010). Open coolers are small tanks, the maximum volume of which is up to approx. 2000 dm³ (DXO DeLaval, 2018).

Engineering calculations of milk and cooling tanks may be performed in a traditional way or numerically with the use of calculation formulas known from the material resistance theory or numerically with the use of, inter alia, finite elements method (Rusiński et al., 2000; Zienkiewicz, 1972; Labocha and Skotny, 2014). The widely used finite elements method is treated in many branches of industry as a standard method which serves for calculation of the carrying capacity of designed structures. The FEM is a precise computational tool, which currently enables geometrical analysis of very complex structures for which application of basic calculation formulas is impossible. Depending on the selected calculation model, the FEM may be linear or non-linear (Labocha and Skotny, 2014). In the linear analysis, a relation between stresses and strains in the material is defined with a simple linear function defined with Hook's law. A good point of this type of analysis is a relatively short time of realization of calculations and a great precision of calculations with regard to elastic strains. When stresses in material exceed the plastic limit (R_p), linear analysis provides erroneous results of calculations and requires application of other tools that include a plastic character of the material. Such tools may be Neuber Rule (Wächter et al., 2017) and non-linear analysis (MNA – Materially Non-linear Analysis), GN (GNA – Geometrical Non-linear Analysis), GMNA – which combines MNA and GNA (Labocha and Skotny, 2014; EN 1993-1-6, 2007).

Values of stresses in material determined empirically, analytically and numerically must be assessed on account of the acceptance criteria. Industry standards, EUROCODES standards for designing building structures or FKM guideline – Analytical Strength Assessment of Components dedicated for mechanical industry, in particular where there are no guidelines concerning calculations of particular types of machines, may be used for assessment of the carrying capacity of construction elements (Rennert et al., 2012; Wächter et al., 2017). The FKM guideline includes a complex calculation algorithm for static and fatigue calculations for steel or aluminum machine components. The algorithm enables assessment of the carrying capacity of welded and non-welded mechanical elements for nominal and local stresses caused by geometrical notches. Bases for the FKM guideline are standards and technical instructions, inter alia: DIN 18800 (2008), Eurocode 3 (EN 1993-1-6, 2007), VDI 2226 (1965) and recommendations of the International Welding Institute (Hobbacher, 2008).

The objective of the paper was to determine circumferential stresses in the milk tank wall with the use of two independent calculation methods and assessment of the level of determined stresses acc. to the criteria of acceptance available in the FKM guideline – Analytical Strength Assessment of Components.

Scope, methods, and conditions of calculations

According to the presented objective of the paper, stresses were determined with analytical calculations based on the calculation formula known from the theory of the strength of materials and numerical calculations made in FEMAP program with solver NX NASTRAN (NASA Structure Analysis).

The object of the research consisted of an open, cylindrical tank for milk storage (Fig. 1) for which the following material and geometrical characteristic was assumed: external diameter (D) - $\varnothing 4000$ mm, wall thickness (t) - 2 mm, height (h) - 3000 mm, material - stainless steel X5CrNi18-10 acc. to EN 10088-2 (2014).

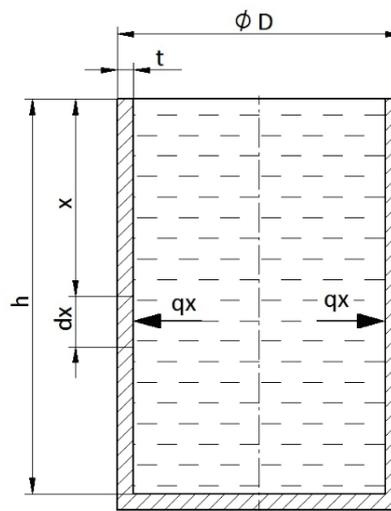


Figure 1. Calculation model of milk tank

Loading of a tank is caused by hydrostatic pressure from the milk column contained in the tank. Hydrostatic pressure acting on the tank wall rises along with the depth and the maximum value is obtained at the bottom according to the relation (Kurowski and Parszewski, 1966):

$$P_h = \rho \cdot g \cdot h \text{ (MPa)} \quad (1)$$

where:

- ρ – milk density assumed for calculations (Jasińska et al., 2011): $1030 \text{ kg}\cdot\text{m}^{-3}$,
- g – gravitational acceleration: $9.81 \text{ m}\cdot\text{s}^{-2}$,
- h – height of the column of liquid 3 m.

Except for the stiffening activation of the bottom (which causes additional bending of the sheath), we may determine in a basic way the highest circumferential stress that occurs in the tank wall (Kurowski and Parszewski, 1966):

$$\sigma_x = \frac{D \cdot q_x}{2 \cdot t} = \frac{D \cdot \rho \cdot g \cdot x}{2 \cdot t} \text{ (MPa)} \quad (2)$$

The maximum circumferential stress in the tank wall at the bottom:

$$\sigma_h = \frac{D \cdot \rho \cdot g \cdot h}{2 \cdot t} \text{ (MPa)} \quad (3)$$

Formula (3) enables calculation of correct values for cross-sections located sufficiently far from the tank bottom, the stiffening activity of which causes additional stresses related to the bending of the shell. The tank is a typical example of the shell structure (EN 1993-1-6, 2007; Labocha and Skotny, 2014; Rusiński et al., 2000; Zienkiewicz, 1972). Thickness of the tank sheet metal is small in comparison to its surface. Numerical model of the tank (CAE – Computer Aided Engineering) is a shell model. Analysis of the degree of utilization, of the three-dimensional coat is taken down to the analysis of the midsurface in other words, the three dimensional model is taken down to the two-dimensional model, in which we will analyse a two-axis flat stress state (Rusiński et al., 2000). The surface of the tank is considered as an ideal shell Impact of imperfection on the shell carrying capacity is not included in calculations (Labocha and Skotny, 2014).

As a comparative criterion for analysis of the degree of utilization, of the tank stresses determined based on Huber-Mises-Hencky theory for the two-axial plane stress state will be used (Rennert et al., 2012; Wächter et al., 2017):

$$\sigma_v = \sqrt{\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2} = \sqrt{\sigma_1^2 - \sigma_1 \sigma_2 + \sigma_2^2} \text{ (MPa)} \quad (4)$$

During the FEM analysis the following assumptions were made - linear static, loading - hydrostatic pressure ($P_h = 0.0303$ MPa), geometrical constraints - edge of the tank bottom is restrained on the circumference. A grid with the number of elements 32046 and dimension 40x40 mm was assumed. Results of calculations carried out with the use of FEM were used as the input data for analysis the aim of which was proving static carrying capacity of the tank wall based on the calculation algorithm FKM (Rennert et al., 2012; Wächter et al., 2017). In order to perform calculations based on the FKM guideline the following sizes characteristic for steel were assumed X5CrNi18-10 acc. to EN 10088-2 (Rennert et al., 2012): standard plastic limit: $R_{e,N} = 220$ MPa, standard tensile strength: $R_{m,N} = 520$ MPa, elongation at rapture: $A = \varepsilon_{ref} = 45\%$, Young module: $E = 210000$ MPa, Poisson number: $\nu = 0.3$. Calculation tensile strength (R_m) and plastic limit of the material (R_p) described are respectively expressed with the relations (5) and (6):

$$R_m = K_{d,m} \cdot K_A \cdot R_{m,N} \text{ (MPa)} \quad (5)$$

$$R_p = K_{d,p} \cdot K_A \cdot R_{e,N} \text{ (MPa)} \quad (6)$$

$$K_{d,m} = \frac{1 - 0,7686 \cdot a_{d,m} \cdot \lg\left(\frac{d_{eff}}{7,5 \text{ mm}}\right)}{1 - 0,7686 \cdot a_{d,m} \cdot \lg\left(\frac{d_{eff,N,m}}{7,5 \text{ mm}}\right)} \text{ (-)} \quad (7)$$

$$K_{d,p} = \frac{1 - 0,7686 \cdot a_{d,p} \cdot \lg\left(\frac{d_{eff}}{7,5 \text{ mm}}\right)}{1 - 0,7686 \cdot a_{d,p} \cdot \lg\left(\frac{d_{eff,N,p}}{7,5 \text{ mm}}\right)} \text{ (-)} \quad (8)$$

where:

- $K_{d,m}, K_{d,p}$ – technological ratios of size. For stainless steel ratios $K_{d,m} = K_{d,p} = 1$
- K_A – anisotropy ratio. For stainless steel $K_A = 1$ (-)
- $a_{d,m}, a_{d,p}$ – material constants (-),
- d_{eff} – effective mean (m),
- $d_{eff,N,m}, d_{eff,N,p}$ – material constants (m).

Computational strength of an element (σ_{SK}) and plastic notch factor (n_{pl}) were determined respectively with the use of the relation (9) and (10) :

$$\sigma_{SK} = n_{pl} \cdot R_p \quad (-) \quad (9)$$

A constructional element does not lose the carrying capacity automatically in the moment when the plastic limit of the material is gained locally (6). This fact is included in the plastic notch factor (n_{pl}), a parameter used for analysis of degree of utilization, of spots where sudden changes of cross-section occur - geometric notches (openings, cuttings, grooves, etc.) :

$$n_{pl} = \min \left(\sqrt{\frac{\varepsilon_{ertr} \cdot E}{R_p}}; K_p \right) \quad (-) \quad (10)$$

where:

- ε_{ertr} – critical relative strain of material (%),
- K_p – plastic ratio of the notch (-).

The plastic notch factor is described with two expressions. The first expression is related to the damage of the structure resulting from local formation of cracks, cracking of material. The second expression - plastic ratio of the notch (K_p) is a parameter related to the global damage resulting from yielding of material:

$$K_p = \frac{L_p}{L_e} \quad (-) \quad (11)$$

where:

- L_p – plastic limit of loading (N),
- L_e – elastic limit of loading (N).

For the constant value of stress in the investigated cross-section ratio $K_p = 1$. Allotting to the plastic notch factor (n_{pl}) a value equal to one, additional reserves of material carrying capacity are not included in the areas of geometrical notches. Austenitic steel $n_{pl} = K_p$ (with regard to high ductility of material).

Next parameter needed for calculations based on the FKM guideline is a safety parameter (j_{ges}) described with the relation (12) (Rennert et al., 2012; Wächter et al., 2017) :

$$j_{ges} = j_S \cdot j_F \quad (-) \quad (12)$$

where:

- j_S – partial safety factor related to loading,
- j_F – partial safety factor related to material.

$$j_F = \max\left(j_m \cdot \frac{R_p}{R_m}, j_p\right) \quad (-) \quad (13)$$

where:

- j_p – safety factor for material for assessment of yielding strength,
- j_m – safety factor for material for assessment of tensile strength.

Values of safety factors (j_p) i (j_m) were presented in table 1.

In case of some loading (e.g. constant value of hydrostatic pressure in a tank), ratio (j_s) assumes value equal to 1. In case of loadings, changing in the time function, for which detailed determination of the stress value is impossible, safety factor (j_s) is calculated based on the principle of the calculus of probability. In case of some loadings, which are randomly generated, the value of the ratio $j_s > 1$ (Rennert et al., 2012; Wächter et al., 2017).

Table 1.
Safety factor (j_p) i (j_m) for material

Specification		Damage results			
		High	Average	Low	
Probability of stresses or stresses combination	High	j_m	2.00	1.85	1.75
		j_p	1.50	1.40	1.30
	Low	j_m	1.80	1.70	1.60
		j_p	1.35	1.25	1.20

Source: Author's own research based on Wächter et al. (2017)

Damage results: high - fatalities, average – device/ machine damage that enables further operation, small - the fault does not exclude the device/machine from exploitation. Damage results referred to the analysed tank – average. In case the tank is unsealed, broken, it is required to set the tank aside from exploitation to the moment of repair. Probability of stress - high. The tank will be often exposed to calculation loading from the hydrostatic pressure.

A prove to the static strength of the tank wall was presented based on calculations of the static degree of utilization (Rennert et al., 2012; Wächter et al., 2017):

$$a_{sk} = \frac{\sigma_V}{\frac{\sigma_{SK}}{j_{ges}}} = \frac{\sqrt{\sigma_x^2 - \sigma_x \sigma_y + \sigma_y^2 + 3\tau_{xy}^2}}{\frac{n_{pl} \cdot R_p}{j_s \cdot \max\left(j_m \cdot \frac{R_p}{R_m}, j_p\right)}} \leq 1 \quad (14)$$

According to the FKM algorithm comparative stresses (σ_V) may result from analytical calculations, FEM analysis or tests.

Results of calculations

The maximum value of hydrostatic pressure (P_h) determines based on the relation (1) is 0.0303 MPa. The highest value of the circumferential stress (σ_h) determined based on the

relation (3) is 30.3 MPa. The highest value of the circumferential stress (σ_v) obtained in the FEM analysis is 30.9 MPa (figure 2).

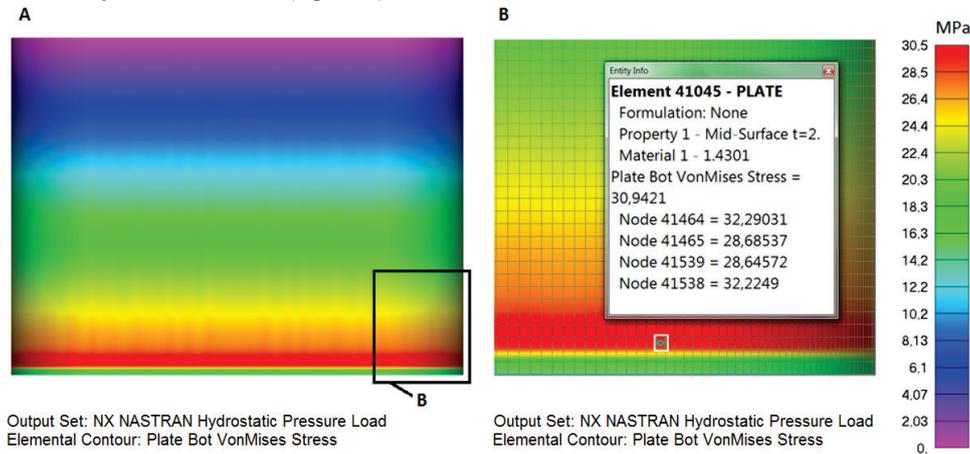


Figure 2. Milk tank – Von Mises stresses: A – Distribution of stresses in the entire tank, B – Distribution of stresses and visualization of meshing – detail B

Based on formula (5) and (6) tensile strength of material was determined – $R_m = 520$ MPa and plastic limit of the tank material – $R_p = 220$ MPa. The maximum value of the reduced stress (σ_v) was read in the distance of 100 mm from the bottom of the tank (fig. 2B) in the location where the tank cross-section is uniform and devoid of the geometrical notch. Thus, (n_{pl}) assumes the value of 1 (Rennert et al., 2012; Wächter et al., 2017). Based on the data included in table 1 partial safety factors assume the following values: $j_m = 1.85$ and $j_p = 1.4$. Based on the formula (13) a partial safety factor for the tank wall material was determined: $j_F = 1.4$. Based on the relation (12) the safety factor for the tank wall: $j_{ges} = 1.4$. A degree of the static utilization of the tank wall (a_{sk}) determined based on the relation (14) is 0.197. The required static utilization $a_{sk} \leq 1$ (14) was maintained. Value 1 in the formula (14) means 100% of effort. The degree of effort of the analysed tank wall is thus 19.7%.

Conclusions

According to the objective of the paper, circumferential stress that occurs in the milk tank wall was determined. Stresses determined with the analytical method based on the expression (3) have the value of $\sigma_h = 30.3$ MPa and stresses determine based on the FEM (4) have a value of $\sigma_v = 30.9$ MPa (figure 2). A difference in the obtained results is small and does not exceed 2%. Both calculation methods may be used as tools for determination of stresses that take place in the tank wall. In the analytical calculations the weight of the tank shell was omitted, as a result of which axial stresses in the tank wall were eliminated. Based on the FKM algorithm a static degree of the tank wall utilization was determined (a_{sk}) which is 19.7 % (14). The tank wall has a considerable carrying capacity reserves.

The FKM guideline is a useful tool that enables assessment of the mechanical structures utilization rate, in particular, where there are no detailed industry standards or design guidelines.

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OCENA PRZYDATNOŚCI ALGORYTMU OBLICZENIOWEGO FKM DO WYZNACZANIA STOPNIA WYŁĘŻENIA ŚCIANKI ZBIORNIKA NA MLEKO

Streszczenie. Celem pracy było wyznaczenie naprężeń obwodowych występujących w ściance otwartego zbiornika na mleko oraz ocena stopnia wyłężenia ścianki w oparciu o algorytm obliczeniowy FKM Guideline – Analytical Strength Assessment of Components, Made of Steel Cast Iron and Aluminium Materials in Mechanical Engineering, którego skrót (FKM) pochodzi od niemieckiej nazwy – Forschungskuratorium für Maschinenbau. Naprężenia wyznaczono w oparciu o obliczenia analityczne oraz obliczenia numeryczne z wykorzystaniem Metody Elementów Skończonych – MES. Obliczenia numeryczne wykonano w programie FEMAP z Solverem NX NASTRAN. Stwierdzono zbliżone wartości naprężeń przy zastosowaniu dwu niezależnych metod obliczeniowych. Różnica uzyskanych wartości naprężeń nie przekracza 2%. W oparciu o algorytm FKM obliczono współczynnik bezpieczeństwa $j_{ges}=1,4$ oraz wyznaczono statyczny stopień wyłężenia ścianki zbiornika $a_{sk}= 19,7\%$.

Słowa kluczowe: mleko, schładzalnik, zbiornik, wyłężenie, przewodnik FKM, współczynnik bezpieczeństwa.

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