THERMAL STATES OF LOADING IN THE ANNULAR PLATES. VARIABLE TEMPERATURE ALONG THE RADIUS. OUTER EDGE FIXED AND INNER EDGE FREE

IATAN I. RADU[1*], POPA T. CARMEN[2], MENGHER RUXANDRA[3]

[1, 3]Polytechnic University of Bucharest – Splaiul Independenţei 313, sector 6, Bucureşti, O.P. 16, cod 060402, România
[2]Valahia University of Targoviste, B-dul Unirii, nr. 2, România

Abstract. The paper discusses the case of an annular plate, being under the action of a radial variable temperature field, but constant on its thickness. In the conditions of the outside outline embedded and that inside free, the expressions of the radial and annular stresses, respectively the radial displacement relation, are specified. The loading is considered below the yield temperature value.

Keywords: annular plate, radial and annular stresses, radial displacement

1. INTRODUCTION

Researchers are permanently looking to asses correctly the mechanical or/and thermal loadings of process equipment. Present conditions impose using less construction materials and providing the safe operation of the equipment during its lifetime. Under real work conditions of the mechanical structures under pressure – pressure and temperature values vary in time; the environment is highly aggressive both chemical and mechanical – these characteristics impose a refiner study of the causes that lead to these loadings so that the dimensioning of the constructive components is correct. Following this manner of thinking the variation of the temperature, in general, but particularly for annular and circular plates, has to be precisely specified, dependent on each technological process. The named example papers [1 ÷ 11], present fully these conditions.

In the paper [1] the assumptions taken into discussed in the analysis of annular plates, thermal loaded were presented. In the present study, the case where the outside edge of the plate is fixed, and that inside free is analyzed. The temperature is considered constant over the plate thickness, but variable along the radius, after various laws, given in the [1, 2] study.

To assess the radial and annular stresses, are taken into account the equalities [1]:

$$\sigma_r(r) = -\frac{E_p \cdot \alpha_T}{r^2} \cdot I_1^{\bullet} + \frac{E_p}{1-\nu_p} \cdot C_{1T}^{\bullet} - \frac{E_p}{\left(1+\nu_p\right) \cdot r^2} \cdot C_{2T}^{\bullet}; \tag{1}$$

$$\sigma_\theta(r) = \frac{E_p \cdot \alpha_T}{r^2} \cdot I_1^{\bullet} - E_p \cdot \alpha_T \cdot \Delta T(r) + \frac{E_p}{1-\nu_p} \cdot C_{1T}^{\bullet} + \frac{E_p}{\left(1+\nu_p\right) \cdot r^2} \cdot C_{2T}^{\bullet}, \tag{2}$$

* Corresponding author, email: r_iatan@yahoo.com

with:

$$I_1^{\bullet} = \int_{r_0}^{r} \Delta T(r) \cdot r \cdot dr . \tag{3}$$

Generally, for an annular plate, the radial displacement in a certain point of the median surface of the plate has the expression [1]:

$$u(r) = \frac{(1+\nu_p)\cdot\alpha_T}{r} \cdot \int_{r_0}^{r} \Delta T(r) \cdot r \cdot dr + C_{1T}^{\bullet} \cdot r + \frac{C_{2T}^{\bullet}}{r}, \tag{4}$$

To establish the expressions of the integration constants the boundary conditions are put:

$$r = r_{cr}; \quad u(r_{cr}) = 0; \quad r = r_0; \quad \sigma_r(r_0) = 0, \tag{5}$$

resulting the expressions of the integration constants, written in the study:

$$C_{1T}^{\bullet} = K_{C1} \cdot \alpha_T \cdot I_2^{\bullet}; \quad C_{2T}^{\bullet} = K_{C2} \cdot \alpha_T \cdot I_2^{\bullet}, \tag{6}$$

with:

$$K_{C1} = -\frac{1-\nu_p^2}{(1+\nu_p)\cdot r_0^2 + (1-\nu_p)\cdot r_{cr}^2}; \tag{7}$$

$$K_{C2} = -\frac{(1+\nu_p)^2 \cdot r_0^2}{(1+\nu_p)\cdot r_0^2 + (1-\nu_p)\cdot r_{cr}^2}; \tag{8}$$

$$I_2^{\bullet} = \int_{r_0}^{r_{cr}} \Delta T(r) \cdot r \cdot dr . \tag{9}$$

The expressions of the radial and annular stresses σ_r and σ_θ, respectively of the radial displacements $u(r)$ take the configurations:

2. TYPES OF THERMAL LOAD

2. 1. Stationary thermal field, independent of the current radius of the plate

The low of variation of the temperature is:

$$\Delta T(r) = T_e - T_0 = \Delta T = \text{ constant,}$$

resulting the stresses:

$$\sigma_r = -\frac{E_p \cdot \alpha_T}{2} \cdot \left\{ 1 - \frac{r_0^2}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{(1+\nu_p)\cdot r^2} \right] \cdot \left(r_{cr}^2 - r^2 \right) \right\} \cdot \Delta T; \tag{10}$$

$$\sigma_\theta = -\frac{E_p \cdot \alpha_T}{2} \cdot \left\{ 1 + \frac{r_0^2}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{(1+\nu_p)\cdot r^2} \right] \cdot \left(r_{cr}^2 - r^2 \right) \right\} \cdot \Delta T, \tag{11}$$

respectively the radial displacement:

$$u(r) = \frac{\alpha_T \cdot \Delta T}{2 \cdot r} \cdot \left[\left(1 + \nu_p\right) \cdot \left(r^2 - r_0^2\right) + \left(K_{C1} \cdot r^2 + K_{C2}\right) \cdot \left(r_{cr}^2 - r_0^2\right) \right]. \tag{12}$$

2. 2. Stationary thermal field, linear dependent of the plate current radius
The variation of the temperature is:

$$\Delta T(r) = \Delta T_{ec}^{r_0} + \left(T_{ep} - T_{ec}^{r_0}\right) \cdot \frac{r}{r_{cr}},$$

for which:

$$\sigma_r = K_{31}^{II} \cdot \Delta T_{ec}^{r_0} + K_{32}^{II} \cdot \left(T_{ep} - T_{ec}^{r_0}\right); \tag{13}$$

$$\sigma_\theta = K_{33}^{II} \cdot \Delta T_{ec}^{r_0} + K_{34}^{II} \cdot \left(T_{ep} - T_{ec}^{r_0}\right), \tag{14}$$

with the notations:

$$K_{31}^{II} = -E_p \cdot \alpha_T \cdot \left\{ \frac{1}{r^2} \cdot k_{21}^i - \left[\frac{K_{C1}}{1 - \nu_p} - \frac{K_{C2}}{\left(1 + \nu_p\right) \cdot r^2} \right] \cdot k_{23}^i \right\}; \tag{15}$$

$$K_{32}^{II} = -E_p \cdot \alpha_T \cdot \left\{ \frac{1}{r^2} \cdot k_{22}^i - \left[\frac{K_{C1}}{1 - \nu_p} - \frac{K_{C2}}{\left(1 + \nu_p\right) \cdot r^2} \right] \cdot k_{24}^i \right\}; \tag{16}$$

$$K_{33}^{II} = -E_p \cdot \alpha_T \cdot \left\{ 1 - \frac{1}{r^2} \cdot k_{21}^i - \left[\frac{K_{C1}}{1 - \nu_p} + \frac{K_{C2}}{\left(1 + \nu_p\right) \cdot r^2} \right] \cdot k_{23}^i \right\}; \tag{17}$$

$$K_{34}^{II} = -E_p \cdot \alpha_T \cdot \left\{ \frac{r}{r_{cr}} - \frac{1}{r^2} \cdot k_{22}^i - \left[\frac{K_{C1}}{1 - \nu_p} + \frac{K_{C2}}{\left(1 + \nu_p\right) \cdot r^2} \right] \cdot k_{24}^i \right\}; \tag{18}$$

$$k_{21}^i = \frac{1}{2} \cdot \left(r^2 - r_0^2\right); \; k_{22}^i = \frac{1}{3 \cdot r_{cr}} \cdot \left(r^3 - r_0^3\right); \tag{19}$$

$$k_{23}^i = \frac{1}{2} \cdot \left(r_{cr}^2 - r_0^2\right); \; k_{24}^i = \frac{1}{3 \cdot r_{cr}} \cdot \left(r_{cr}^3 - r_0^3\right), \tag{20}$$

respectively:

$$u(r) = k_{31}^{II} \cdot \Delta T_{ec}^{r_0} + k_{32}^{II} \cdot \left(T_{ep} - T_{ec}^{r_0}\right), \tag{21}$$

with:

$$k_{31}^{II} = \alpha_T \cdot \left[\frac{1 + \nu_p}{r} \cdot k_{21}^i + \left(K_{C1} \cdot r + \frac{K_{C2}}{r} \right) \cdot k_{23}^i \right]; \tag{22}$$

$$k_{32}^{II} = \alpha_T \cdot \left[\frac{1+\nu_p}{r} \cdot k_{22}^{i} + \left(K_{C1} \cdot r + \frac{K_{C2}}{r} \right) \cdot k_{24}^{i} \right]. \tag{23}$$

2. 3. Centrally heated or cooled plate. Stationary thermal field, with parabolic variation
The expression of the thermal gradient is:

$$\Delta T(r) = \Delta T_{ec}^{r_0} \cdot \left(1 - \frac{r^2}{r_{cr}^2} \right),$$

obtaining further:

$$\sigma_r = K_{31}^{III} \cdot \Delta T_{ec}^{r_0}; \qquad \sigma_\theta = K_{32}^{III} \cdot \Delta T_{ec}^{r_0}; \tag{24}$$

$$K_{31}^{III} = -E_p \cdot \alpha_T \cdot \left\{ \frac{k_{25}^{i}}{r^2} + \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{26}^{i} \right\}; \tag{25}$$

$$K_{32}^{III} = -E_p \cdot \alpha_T \cdot \left\{ 1 - \frac{r^2}{r_{cr}^2} - \frac{k_{25}^{i}}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} + \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{26}^{i} \right\}; \tag{26}$$

$$k_{25}^{i} = \frac{1}{2} \cdot \left(r^2 - r_0^2 \right) \cdot \left[1 - \frac{1}{2 \cdot r_{cr}^2} \cdot \left(r^2 + r_0^2 \right) \right]; \tag{27}$$

$$k_{26}^{i} = \frac{1}{4} \cdot \left(r_{cr}^2 - r_0^2 \right) \cdot \left(1 - \frac{r_0^2}{r_{cr}^2} \right); \tag{28}$$

$$u(r) = k_{31}^{III} \cdot \Delta T_{ec}^{r_0}; \tag{29}$$

$$k_{31}^{III} = \alpha_T \cdot \left[\frac{1+\nu_p}{r} \cdot k_{25}^{i} + \left(K_{C1} \cdot r + \frac{K_{C2}}{r} \right) \cdot k_{26}^{i} \right]. \tag{30}$$

2. 4. Peripheral heated or cooled plate. Stationary thermal field, with exponential variation
The low of temperature is:

$$\Delta T(r) = \Delta T_{ep} \cdot \left(\frac{r}{r_{cr}} \right)^n; \qquad \Delta T_{ep} = T_{ep} - T_0 \, ,$$

and further:

$$\sigma_r = K_{31}^{IV} \cdot \Delta T_{ep}; \quad \sigma_\theta = K_{32}^{IV} \cdot \Delta T_{ep}; \tag{31}$$

$$K_{31}^{IV} = -E_p \cdot \alpha_T \cdot \left\{ \frac{k_{27}^{i}}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} + \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{28}^{i} \right\}; \tag{32}$$

$$K_{32}^{IV} = E_p \cdot \alpha_T \cdot \left\{ \frac{k_{27}^i}{r^2} - \left(\frac{r}{r_{cr}} \right)^n + \left[\frac{K_{C1}}{1-\nu_p} + \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{28}^i \right\}; \tag{33}$$

$$k_{27}^i = \frac{1}{(n+2) \cdot r_{cr}^n} \cdot \left(r^{n+2} - r_0^{n+2} \right); \tag{34}$$

$$k_{28}^i = \frac{1}{(n+2) \cdot r_{cr}^n} \cdot \left(r_{cr}^{n+2} - r_0^{n+2} \right); \tag{35}$$

$$u(r) = k_{31}^{IV} \cdot \Delta T_{ep}; \tag{36}$$

$$k_{31}^{IV} = \alpha_T \cdot \left[\frac{1+\nu_p}{r} \cdot k_{27}^i + \left(K_{C1} \cdot r + \frac{K_{C2}}{r} \right) \cdot k_{28}^i \right]. \tag{37}$$

2. 5. Combined thermal fields (one independent of radius and one with parabolic variation, descending from the plate center towards the periphery)

The low of variation of the temperature is:

$$\Delta T(r) = \Delta T_{ec}^{r_0} \cdot \left(1 - \frac{r^2}{r_{cr}^2} \right) + \Delta T_{ep},$$

for which:

$$\sigma_r = K_{31}^V \cdot \Delta T_{ec}^{r_0} + K_{32}^V \cdot \Delta T_{ep}; \qquad \sigma_\theta = K_{33}^V \cdot \Delta T_{ec}^{r_0} + K_{34}^V \cdot \Delta T_{ep}; \tag{38}$$

$$K_{31}^V = -E_p \cdot \alpha_T \cdot \left\{ \frac{k_{29}^i}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{211}^i \right\}; \tag{39}$$

$$K_{32}^V = -E_p \cdot \alpha_T \cdot \left\{ \frac{k_{210}^i}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{212}^i \right\}; \tag{40}$$

$$K_{33}^V = E_p \cdot \alpha_T \cdot \left\{ \frac{k_{29}^i}{r^2} - 1 + \frac{r^2}{r_{cr}^2} + \left[\frac{K_{C1}}{1-\nu_p} + \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{211}^i \right\}; \tag{41}$$

$$K_{34}^V = E_p \cdot \alpha_T \cdot \left\{ \frac{k_{210}^i}{r^2} - 1 + \left[\frac{K_{C1}}{1-\nu_p} + \frac{K_{C2}}{\left(1+\nu_p\right) \cdot r^2} \right] \cdot k_{212}^i \right\}; \tag{42}$$

$$k_{29}^i = \frac{1}{2} \cdot \left(1 - \frac{r^2 + r_0^2}{2 \cdot r_{cr}^2} \right) \cdot \left(r^2 - r_0^2 \right); \quad k_{210}^i = \frac{1}{2} \cdot \left(r^2 - r_0^2 \right); \tag{43}$$

$$k^{i}_{211} = \frac{1}{2}\cdot\left(1 - \frac{r^{2}_{cr} + r^{2}_{0}}{2\cdot r^{2}_{cr}}\right)\cdot\left(r^{2}_{cr} - r^{2}_{0}\right);\ k^{i}_{212} = \frac{1}{2}\cdot\left(r^{2}_{cr} - r^{2}_{0}\right); \tag{44}$$

$$u(r) = k^{V}_{31}\cdot\Delta T^{r_0}_{ec} + k^{V}_{32}\cdot\Delta T_{ep}; \tag{45}$$

$$k^{V}_{31} = \alpha_T\cdot\left[\frac{1+\nu_p}{r}\cdot k^{i}_{29} + \left(K_{C1}\cdot r + \frac{K_{C2}}{r}\right)\cdot k^{i}_{211}\right]; \tag{46}$$

$$k^{V}_{32} = \alpha_T\cdot\left[\frac{1+\nu_p}{r}\cdot k^{i}_{210} + \left(K_{C1}\cdot r + \frac{K_{C2}}{r}\right)\cdot k^{i}_{212}\right]. \tag{47}$$

2. 6. Combined thermal fields (one independent of radius and one with exponentially variation, increasing from the plate center towards the periphery)

Respect this situation we accept the following low:

$$\Delta T(r) = \Delta T^{r_0}_{ec} + \left(T_{ep} - T^{r_0}_{ec}\right)\cdot\left(\frac{r}{r_{cr}}\right)^{n},$$

leading to:

$$\sigma_r = K^{VI}_{31}\cdot\Delta T^{r_0}_{ec} + K^{VI}_{32}\cdot\left(T_{ep} - T^{r_0}_{ec}\right); \tag{48}$$

$$\sigma_\theta = K^{VI}_{33}\cdot\Delta T^{r_0}_{ec} + K^{VI}_{34}\cdot\left(T_{ep} - T^{r_0}_{ec}\right); \tag{49}$$

$$K^{VI}_{31} = -E_p\cdot\alpha_T\cdot\left\{\frac{k^{i}_{213}}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{\left(1+\nu_p\right)\cdot r^2}\right]\cdot k^{i}_{215}\right\}; \tag{50}$$

$$K^{VI}_{32} = -E_p\cdot\alpha_T\cdot\left\{\frac{k^{i}_{214}}{r^2} - \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{\left(1+\nu_p\right)\cdot r^2}\right]\cdot k^{i}_{216}\right\}; \tag{51}$$

$$K^{VI}_{33} = E_p\cdot\alpha_T\cdot\left\{\frac{k^{i}_{213}}{r^2} - 1 + \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{\left(1+\nu_p\right)\cdot r^2}\right]\cdot k^{i}_{215}\right\}; \tag{52}$$

$$K^{VI}_{34} = E_p\cdot\alpha_T\cdot\left\{\frac{k^{i}_{213}}{r^2} - \left(\frac{r}{r_{cr}}\right)^{n} + \left[\frac{K_{C1}}{1-\nu_p} - \frac{K_{C2}}{\left(1+\nu_p\right)\cdot r^2}\right]\cdot k^{i}_{215}\right\}; \tag{53}$$

$$k^{i}_{213} = \frac{1}{2}\cdot\left(r^2 - r^{2}_{0}\right);\quad k^{i}_{214} = \frac{1}{n+2}\cdot\frac{1}{r^{n}_{cr}}\cdot\left(r^{n+2} - r^{n+2}_{0}\right); \tag{54}$$

$$k^{i}_{215} = \frac{1}{2}\cdot\left(r^{2}_{cr} - r^{2}_{0}\right);\quad k^{i}_{216} = \frac{1}{n+2}\cdot\frac{1}{r^{n}_{cr}}\cdot\left(r^{n+2}_{cr} - r^{n+2}_{0}\right); \tag{55}$$

$$u(r) = k_{31}^{VI} \cdot \Delta T_{ec}^{r_0} + k_{32}^{VI} \cdot \left(T_{ep} - T_{ec}^{r_0} \right); \tag{56}$$

$$k_{31}^{VI} = \alpha_T \cdot \left[\frac{\left(1 + \nu_p\right) \cdot k_{213}^i}{r} + \left(K_{C1} \cdot r + \frac{K_{C2}}{r} \right) \cdot k_{215}^i \right]; \tag{57}$$

$$k_{32}^{VI} = \alpha_T \cdot \left[\frac{\left(1 + \nu_p\right) \cdot k_{214}^i}{r} + \left(K_{C1} \cdot r + \frac{K_{C2}}{r} \right) \cdot k_{216}^i \right]. \tag{58}$$

2.7. Stationary thermal field, with exponential variation

The expression of the thermal gradient according with this case is:

$$\Delta T(r) = \Delta T_{ep} + \Delta T_{ec}^{r_0} \cdot \left(1 - \frac{r}{r_{cr}} \right)^n,$$

the magnitudes which serve to the calculation being:

$$\sigma_r = K_{31}^{VII} \cdot \Delta T_{ec}^{r_0}; \quad \sigma_\theta = K_{32}^{VII} \cdot \Delta T_{ec}^{r_0}; \tag{59}$$

$$K_{31}^{VII} = -E_p \cdot \alpha_T \cdot \left\{ \frac{k_{217}^i}{r^2} - \left[\frac{K_{C1}}{1 - \nu_p} - \frac{K_{C2}}{\left(1 + \nu_p\right) \cdot r^2} \right] \cdot k_{218}^i \right\}; \tag{60}$$

$$K_{32}^{VII} = E_p \cdot \alpha_T \cdot \left\{ \frac{k_{217}^i}{r^2} - e^{K_T^{\bullet} \cdot r} + \left[\frac{K_{C1}}{1 - \nu_p} + \frac{K_{C2}}{\left(1 + \nu_p\right) \cdot r^2} \right] \cdot k_{218}^i \right\}; \tag{61}$$

$$k_{217}^i = \frac{K_T^{\bullet} \cdot r - 1}{\left(K_T^{\bullet}\right)^2} \cdot \left(e^{K_T^{\bullet} \cdot r} - e^{K_T^{\bullet} \cdot r_0} \right) \cdot \Delta T_{ec}^{r_o}; \tag{62}$$

$$k_{218}^i = \frac{K_T^{\bullet} \cdot r_{cr} - 1}{\left(K_T^{\bullet}\right)^2} \cdot \left(e^{K_T^{\bullet} \cdot r_{cr}} - e^{K_T^{\bullet} \cdot r_0} \right) \cdot \Delta T_{ec}^{r_0}; \tag{63}$$

$$u(r) = k_{31}^{VII} \cdot \Delta T_{ec}^{r_0}; \tag{64}$$

$$k_{31}^{VII} = \alpha_T \cdot \left[\frac{\left(1 + \nu_p\right)}{r} \cdot k_{217}^i + \left(K_{C1} \cdot r + \frac{K_{C2}}{r} \right) \cdot k_{218}^i \right]. \tag{65}$$

Notations used: k, K – factors of influence; n – arbitrarily chosen number; r – current radius ($r \in \left[r_o ; r_{cr} \right]$); r_{cr}, r_0 – radius of outside outline, respectively of that inside of the plate; $u(r)$ – radial displacement; $C_{1T}^{\bullet}$, $C_{2T}^{\bullet}$ – integration constants; E_p – modulus of longitudinal elasticity of the plate material; $I_1^{\bullet}$, $I_2^{\bullet}$ – helping magnitudes of calculation; T_0, T_e – temperature of the external medium and temperature of exploitation; T_{ep} – temperature of exploitation of the plate, for the external contour; ν_p – coefficient of transverse contraction of the material; α_T – factor of thermal deformation; ΔT, $\Delta T(r)$ – thermal gradient (constant) and thermal gradient at the level at one current radius; $\Delta T_{ec}^{r_0}$, ΔT_{ep} – thermal gradient at the level at centre of the plate, respectively at the external level of the plate; σ_r, σ_θ – radial and annular stresses.

3. CONCLUSIONS

The above expressions allow the evaluation of the stresses and deformations states in the annular flat plates, subjected to the action of a field of temperature having variation along the radius, according to various laws, but constant on thickness. It is noted that in all the deduced relations, the plate thickness is not present. The calculation temperature is considered below the value characteristic to the yield.

The possible examples, for individual practical cases, can highlight the specific differences.

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