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Research Article

Structural analysis of embedded hollow tubes on straight and curved platforms under thermal loads

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ABSTRACT

Tube systems are widely used in heat transfer and intensive research is being done on positioning tubes on a platform. The platform structure is constantly exposed to thermal changes under operating conditions and the resulting stresses cause damage to existing systems. In this study, 8 thin-walled tubes were positioned on flat and curved platforms that were widely used and the stress behavior under thermal effects was investigated. Finite element analysis was used, and steady-state thermal condition was considered in the numerical investigation. The effects of temperature difference between platform surfaces and the thermal conductivity at the tube surfaces were investigated. It has been determined that the stress on the platform is higher than the stress on the tubes and the increase in the temperature difference on the platform surfaces increases the stress drastically. The increased thermal conductivity coefficient on the tube surface reduced the stresses on the platform and increased fatigue performance. Flat platform has lower contact pressure and platform stresses and better fatigue behavior. Results are discussed in detail.

1. Introduction

Tube systems are generally used to obtain heat from solar energy or to transfer heat from one heat source to another. Environmental conditions and thermal effects are dominant, and these factors exhibit an unstable attitude. Considering these factors, different geometric shapes, material types, various surface conditions and mounting structures are investigated. Studies in the literature focus on increasing efficiency in thermal solar panels, especially on thermal performance. Tube systems were systematically examined on the panels, and various geometric and material analyses were made. Flat plate was the most preferred in terms of ease of maintenance and production and cost in various tube panel systems such as flat plate, compound parabolic, evacuated tube, parabolic trough, Fresnel lens, parabolic bowl and heliostat field collectors [1-2]. The iso-scale trapezoidal absorber plate [3] developed for collector efficiency in flat plates reached 62% efficiency. Concentrated radiation applied to the tube along the focal line [4] increased the efficiency. Efficiency increased when the flow [5] was supported by homogeneous temperature distribution and simpler tube system structures [6] can be used to achieve homogeneous temperature distribution, further reducing the production cost. The numerical investigation method [7] is sufficient and efficient to investigate the properties of thermal devices, and this method has been applied with the ANSYS simulation program [8] to avoid large deformation of absorbent flat plates. A 3D mathematical model of flat plate collectors [9] has been developed and applied in different collector types and flow conditions. The finite volume method (FVM) and Monte Carlo Ray-Trace (MCRT) [10] were combined for 3D computational solar collector analysis to obtain detailed flow and temperature results. The mechanical behavior of potential sealing materials [11] used in tube connections were investigated under the effects of atmospheric pressure and thermal expansion. In the study using the finite element method, it was determined that the low temperature bonding process provided sufficient strength. In the investigation of the heat losses between the absorber and the glass, the effects of the temperature difference were investigated [12] and it was determined that the thermal expansion and stresses formed affect the insulating epoxy material. The thermal stress analysis of the tube receiver [13] with focused radiation was investigated for different material conditions and it was more appropriate to use

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copper material instead of stainless steel. For a parabolic collector, thermal stress analysis [14] was carried out on absorber tubes and it was seen that the highest tube deformation occurred in the supports. For a circular tube, heat transfer and thermal stresses [15] were investigated and it was determined that there was a relationship between the resulting stresses and the Biot number. Thermal-mechanical effects [16] have been investigated in the design of a central receiver for tubes. It [17-19] was seen that the bearing effects dominate the stress formation in the tube, and it was determined that the axial stresses formed were much larger than the stresses in the radial direction. It was predicted that thermal bending can be prevented with the support type. The thermal loads [20] for collector tubes in solar power buildings, which are complex to measure experimentally, were investigated with computer aided numerical methods and it was seen that thermal effects doubled the maximum equivalent stress. A new bayonet tube receiver [21] was designed to avoid the stress increase and compared it with a simple solar collector tube. Von-Mises stresses were significantly reduced as a result of the eccentricity of the bayonet tube. In the thermal stress analysis of bimetallic receivers, the double-layer absorber tube [22] created less stress than the single-layer absorber tube. Thermal and mechanical effects [23] were investigated in the absorber tube of the parabolic trough solar collector (PTSC) made of steel, copper, aluminum, Cu-Fe and four-layer laminate (Cu-Al-SiC-Fe). Although steel is strong in terms of strength, copper shows better thermal effects in thermal conditions. The most optimal material in all conditions was the four-layer laminate and the deflection in the tube was reduced by up to 49% compared to standard steel. In the solar tower research with molten salt receiver, it [24] was observed that the stress distribution and the inner-outer wall temperature difference distribution were similar. The similarity of the stress formed in the tube and the temperature distribution [25] was also seen in another study examining the deformation and stress errors in the absorber tube of parabolic trough collectors. The radial thermal stresses [26] occurred so low that they could be neglected in the thermal stress analysis for non-solar receiver tubes. It has been emphasized that different designs continue to be made in flat and curved panel systems and that mechanical effects in designs should be examined structurally.

In this study, platforms designed as flat and curved and the tubes connected between them were examined considering the thermal-mechanical effects. The effect of the temperature difference at the pipe ends and the heat transfer coefficient, which were known as the dominant effect of the working and environmental conditions, on the tube surfaces has been investigated. The results obtained show where and how intense the stresses were as a result of thermal effects. Fatigue results, which took up little space in the literature, were made in detail with the fatigue analysis applied in this study, and the working life and safety were shown in the results.

2. Method and Tube System Models

It is difficult to produce thin-walled tube systems used in heat transfer and to examine their various parameters. Parametric studies should be carried out in these systems operating under variable temperature and convection effects. In the literature summary, since experimental studies have difficulties in thermal-mechanical investigations, the finite element method was used in this study because it has provided ease of parametric analysis. ANSYS package software was used in the research. A numerical model was created for the finite element method and the stresses created by the temperature and convection effects in the tube were investigated by defining the ideal boundary conditions.

Formation of the finite element model to be used in the analysis dominantly affects the solution accuracy. Therefore, a validation study was carried out before examining the tubes and the results were compared with an analytical solution found in the literature. In Figure 1, one tube used for the validation study was examined in the bending condition. The hollow tube has an inner radius of 35 mm and an outer radius of 37 mm. For the 800 mm long tube, the back surface was fixed and a force of 100 N was applied on the front surface for the bending condition. The bending stress for this condition was shown in Equation (1).

M was the moment due to the force; c was the distance between the cylinder centre and the cylinder outer surface; I was the moment of inertia for the cylinder geometry and was shown in Equation (2).

Thermal tube profiles were prepared in two different mounting arrangements and computer-aided models were created. The tubes are the same as the validation study model shown in Figure 1.

$$\sigma_{analytical} = \frac{M.c}{I} \quad (1)$$

$$I = \frac{\pi}{4}(r_{out}^4 - r_{in}^4) \quad (2)$$

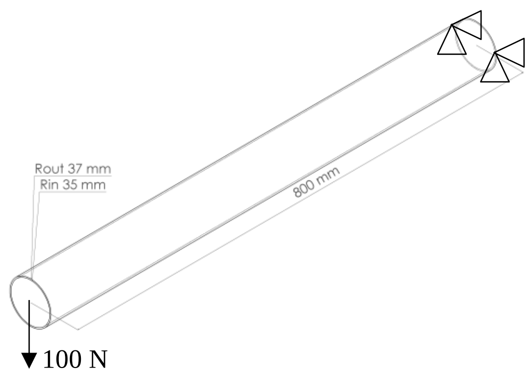

Figure 1. The used validation model

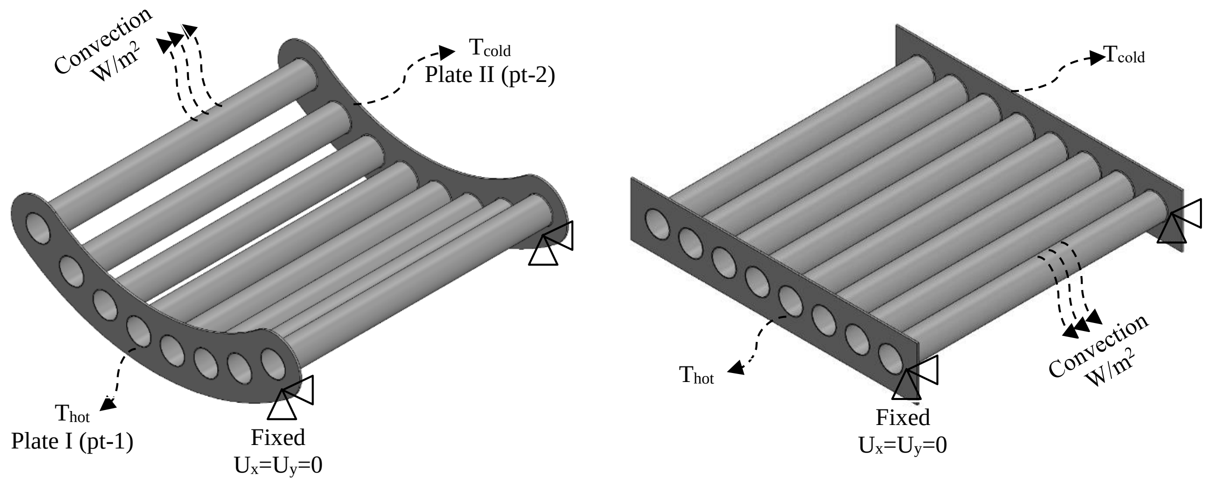

Figure 2. Curved and flat tube platforms and boundary conditions

Central distance between tubes are 100 mm. The used plate dimensions were 860×160×5 mm. Thermal and structural boundary conditions were given in Figure 2. T_{hot}=80°C was used and it was changed to observe temperature difference effects. T_{cold} was set as 22°C, and it was constant in whole analyses. Convection on outer surface of tubes was considered. Side edges of platforms were fixed in structural analyses and bonded contact was used in contact definition. The used contact was suitable for the assembly of tubes and platforms. Standard steel properties were [27] used to define material properties that have modulus of elasticity 200 GPa, Poisson ratio of 0.3 and thermal expansion coefficient of 1.2×10^{-6}/°C. Modulus of elasticity and thermal expansion coefficient [28-30] were used as constants, since tubes were not studied at high temperature ranges and the mechanical-thermal properties of the steel material did not vary much up to 200°C. Stress results were given in Von-Mises stresses. The used stress formulation [27, 31] was given in Equation (3). Soderberg fatigue theory [32-33] was used in fatigue analyses, and it was given in Equation (4).

$$\sigma_{mises} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \quad (3)$$

$$\frac{\sigma_a}{S_e}+\frac{\sigma_m}{S_y}=\frac{1}{n} \quad (4)$$

σ_1 , σ_2 and σ_3 were principal stresses, σ_a and σ_m are alternating and mean stresses. For fatigue analysis, The used parameters and coefficients [34] were; standard strength coefficient (σ_f'), 920 MPa, strength exponent (b), -0.106, ductility coefficient (ϵ_f'), 0.213, ductility exponent (c), -0.47, cyclic strength (K'), 1000 MPa, cyclic strain hardening exponent (n') , 0.2 and yield strength (S_y), 250 MPa.

3. Results and Discussion

For the verification study shown in Figure 1, the stress result available in the literature [27, 35] was calculated in Equation (1). The tensile stress formed in the middle of the tube geometry was found to be 5.04 MPa. The result of the finite element analysis was shown in Figure 3. The result obtained was similar to the analytical solution and the inspection method can be used to calculate the tube stress.

Figure 4 shows the stress and contact pressure due to convection for the curved and flat platform. Platform geometry has the highest stress value of all convection results. Another study [36] in the literature stated that a similar stress concentration occurs on the platform surface and its edges. The applied convection reduced the stress and contact pressure. There was no direct correlation between increasing convection value and decreasing stress value.

The application of convection only to the tube outer surfaces was more effective in reducing the stresses in the tube in Figure 4. Locally occurring high stresses are much lower in most sections. However, the highest values were used in the graph, since the onset of fracture mostly occurred where local stress values were high. Considering the convection effects for the flat platform, the stresses decreased similar to the curved structure. Although the plate (pt-1) stress and contact pressure were higher on the curved platform, the stress within the tube occurred more on the flat platform. Using the curved platform was safer in terms of stresses on the tube body.

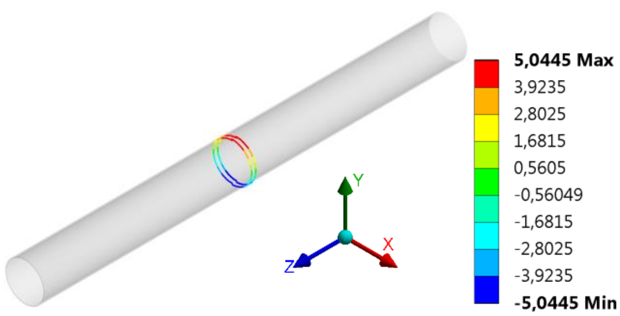

Figure 3. Bending (axial) stresses of a hollow cylinder in the middle of the length (in MPa)

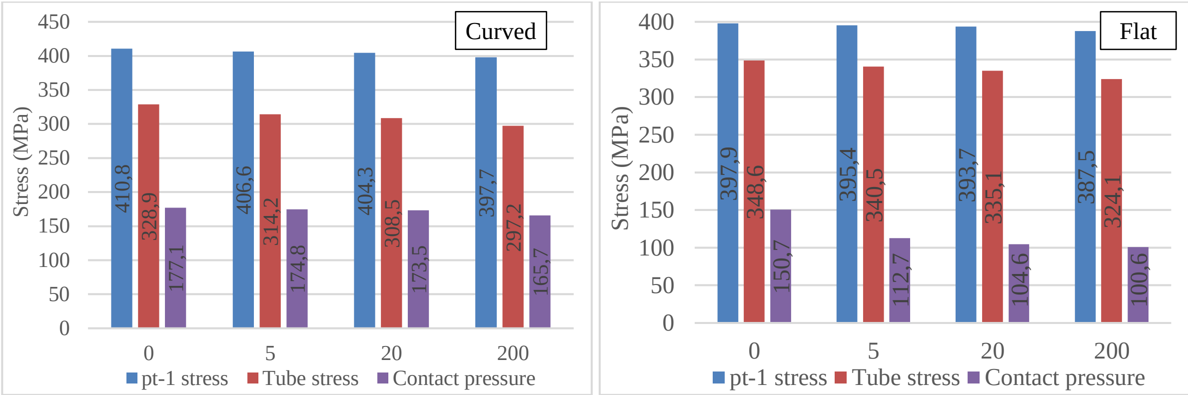

Figure 4. Effect of convection coefficient (0, 5, 20, 200 W/m^2.°C) on Von-Mises stresses and contact pressure in curved and flat system components

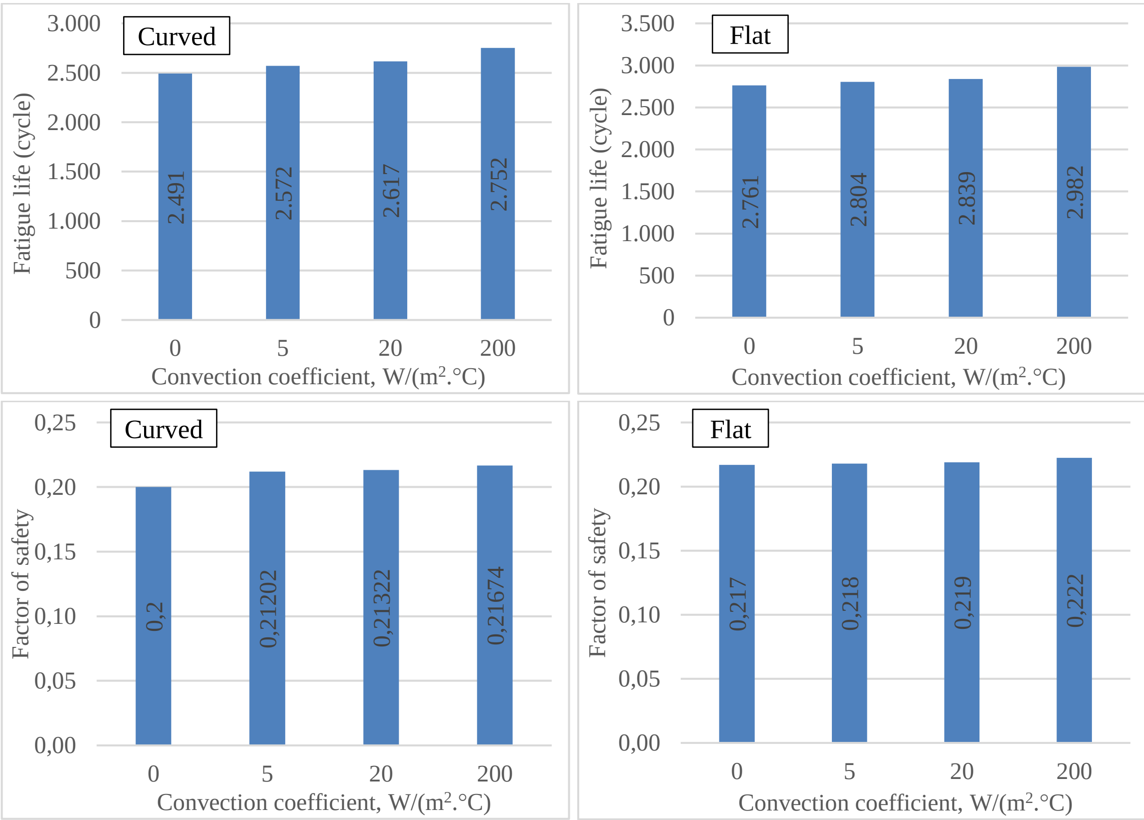

Figure 5. Effect of convection on fatigue life and factor of safety in curved and flat system

Figure 5 showed fatigue life and safety factor for full load/unload condition on curved and flat platform. The stresses were decreased by the convection effect and accordingly the fatigue life and safety factor increased. As the convection coefficient increased from 0 W/m^2.°C to 200 W/m^2.°C, the fatigue life increased 10% and the safety factor increased by 8% on the curved platform. Increased convection on flat platform increased 8% fatigue life and 2.5% safety factor. Flat platform showed more positive effect in terms of fatigue behavior. It was observed that the convection effect and the increase in fatigue results were not directly proportional.

The stresses occurring at the contact edge of the tube and the curved/flat platform were shown in Figure 6. While the stresses on the side edges were higher, the stress values on the lower and upper edges were lower. Stress values decreased with the effect of convection. The difference between the 5, 20 and 200 W/m^2 convection values was small. As a result of the convection, the stresses decreased 6% on the curved platform and 8% on the flat platform.

The stresses formed as a result of the effect of different temperature differences were shown in Figure 7. Convection value was used as 0 W/m^2.°C. The increase in temperature difference predominantly caused an increase in stresses and contact pressure. As the pt-1 temperature increased from 80°C to 120°C, stress value on platform increased by 70%.

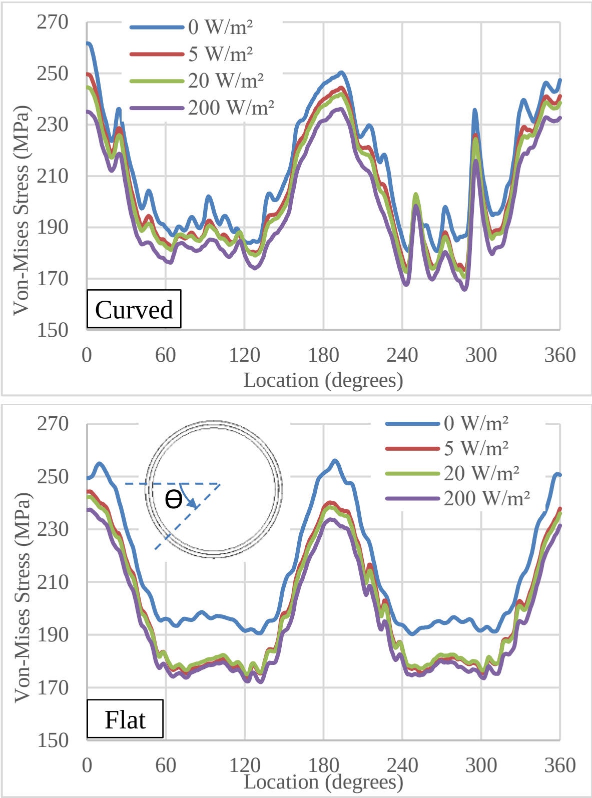

Figure 6. Effect of convection on Von-Mises stress distribution at circumference of 4th tube edge

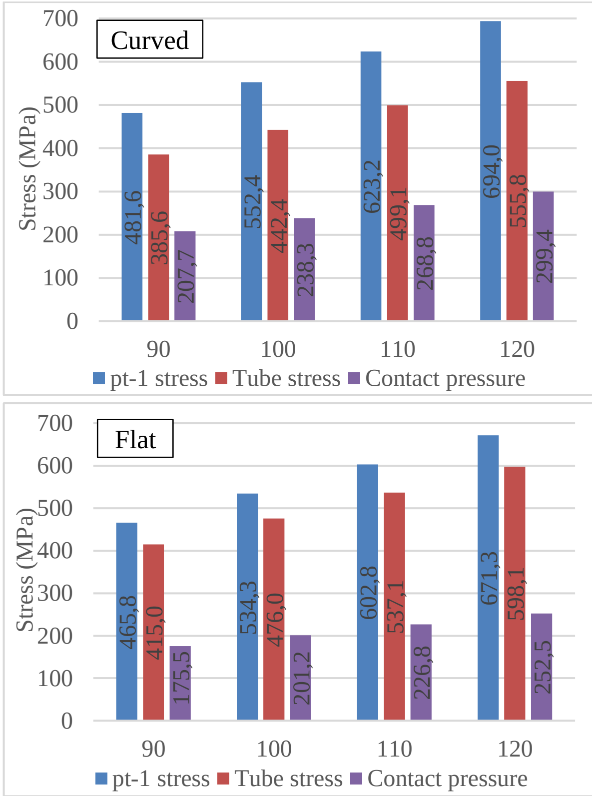

Figure 7. Effect of pt-1 plate temperature (90, 100, 110 and 120°C) on Von-Mises stresses and contact pressure in curved and flat system components

The fact that the increase rate has been higher than the other results was due to the support effects on the platform in Figure 7. In the curved platform, the platform stress and contact pressure were higher, and the tube stress was lower than the flat platform.

The effect of pt-1 temperature for fatigue behaviour was shown in Figure 8. Higher stresses due to increasing temperature difference have been found to shorten the fatigue life. Increased temperature difference from 80°C to 120°C reduced fatigue life by 61% and coefficient of safety by 30% on both platforms.

Figure 9 showed the stresses that occurred at the edge of the tube as a result of the temperature difference. The temperature distribution in the platform results was similar and it was determined that the values increased predominantly as a result of the temperature change. Higher stresses were observed at the lateral edges of the tube contact area, and lower stresses were observed in the lower-upper contact edge region. The use of bonded contacts caused small fluctuations in the stress results, and this seems more evident on the curved platform.

4. Conclusions

In this study, the thermal-mechanical properties of a tube system operating under thermal conditions on two different platforms were investigated by computer aided analysis. The effects of temperature difference and convection coefficient in operating conditions were investigated and the results were shown with graphics. If the main findings of the study are summarized;

- Increasing the convection coefficient has a reducing effect on the stress, increased the fatigue life and safety factor, but this effect is quite low.
- Local contact stresses and bearing effects dominate the stress due to thermal expansion.
- The variation of stresses caused by convection is not directly proportional.
- While tube stress is higher in flat platform, platform stress and contact pressure are lower.
- The fatigue behaviour of the flat platform is longer and safer than the curved platform.
- The increase in temperature difference predominantly caused an increase in stresses and contact pressure.
- Changing the platform temperature from 80°C to 120°C increased the stresses by 70%, reduced the fatigue life by 61% and the safety factor by 30%.

The findings show that thermal-mechanical examination should be done for each new design. Numerical methods are sufficient in terms of both solution time and accuracy.

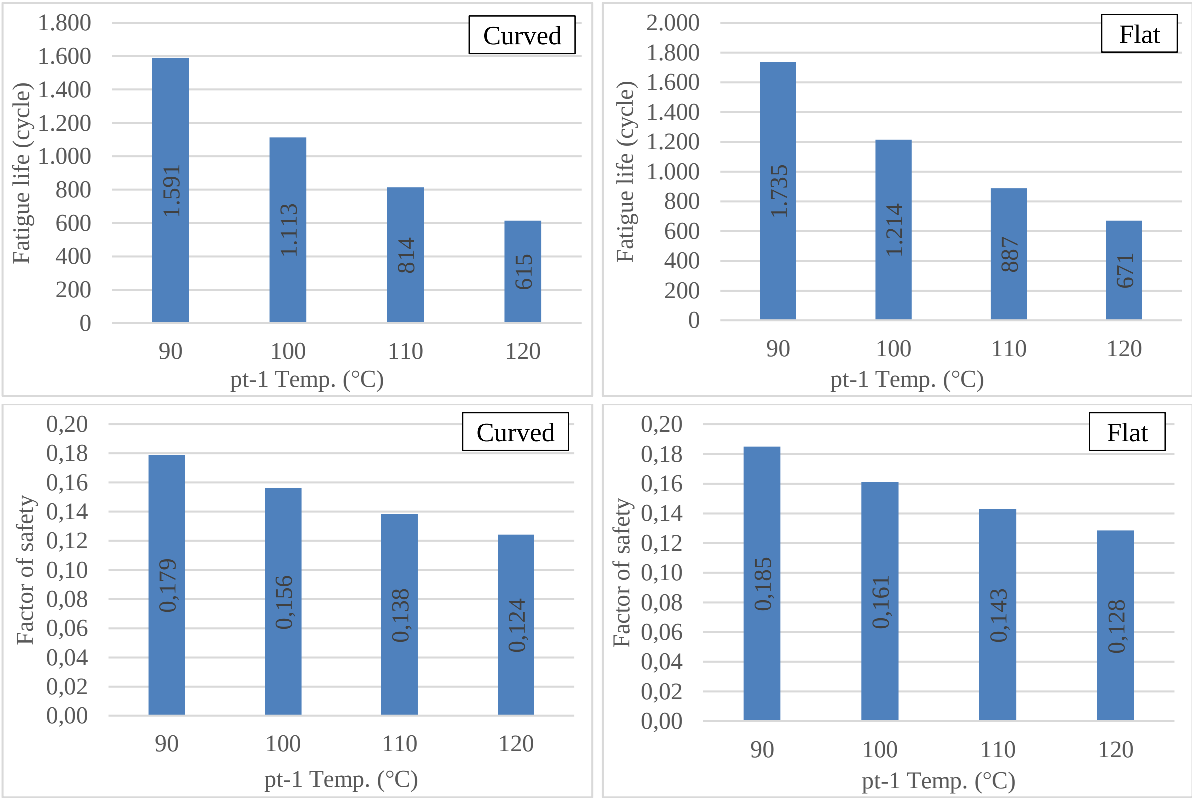

Figure 8. Effect of pt-1 plate temperature on fatigue life and factor of safety in curved and flat system

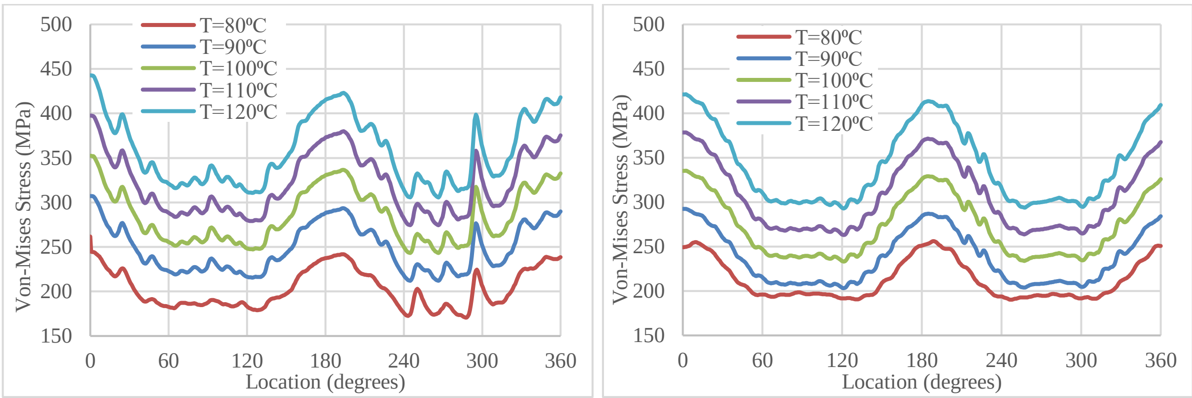

Figure 9. Effect of pt-1 plate temperature on Von-Mises stress distribution at circumference of 4th tube edge at curved and flat system

Declaration

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

M.M. Yavuz performed the analysis and wrote the whole manuscript.

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