The effect of the eccentricity of the annular fin in the bundle of fins exposed to flow on its thermal stresses

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ABSTRACT

In this paper, the effect of the passed fluid flow around a fin in the bundle of annular fins with different eccentricity on thermal stresses created in it is discussed. To solve the turbulent fluid flow equations and thermal stress in solid, the volume element with k-ε model and finite element methods are used, respectively. The results are obtained for 2 fin spacing and 4 heights of fins. Then, in each fin height, the effect of 5 eccentricities on decrease of thermal stress are considered. The results show that at each fin height there is an optimal eccentricity for which the thermal stress in the fin reaches its minimum value. The results show that the maximum decrease of thermal stress in optimal eccentricity related to fin height 4mm for both fin spacing of 4 mm and 8mm are 30 , 35% respectively. According to the results of this paper, although the difference between both pressure drop and heat transfer values in two eccentricity optimal case and concentric case are negligible, thermal stress reduction is observable.

KEYWORDS

Finite element method, Finite volume method, eccentricity, thermal stress, turbulent flow

1. Introduction

Fins are an engineering tool that is used in various industries and they are suitable for increasing and reducing heat transfer from the surface. The research on annular fins bundle can be divided into two general categories. The first category is researches done without flow and eccentricity. The second category studied the heat transfer in the fin with the flow and with or without eccentricity. The following, some of the researches on the heat transfer in the fin and bundles of the fin. In 2015, Chi Chan Wang [1] conducted an experimental study of the performance of tube-fin heat exchangers with simple, window, and half deep fin arrangements. He performed a comparative study on 18 different samples with the number of tube rows N = 1, N = 2, and N = 4. The results of his study showed that at state N = 1 with a fin pitch of less than 1.6 mm, the heat transfer coefficient for the window fin geometry is slightly higher than the simple fin geometry and the half-deep fin geometry. In 2018, Hosseini et al. [2] studied the effect of flow on thermal stresses and strains in the annular fin. They compared thermal stress value of the fin in two general states without and with the fluid flow around a fin. In 2020, Hosseini et al. [3] also compared the effect of two laminar and turbulent flow regimes on thermal stresses and strains in an annular fin. By comparing these two flow regimes, they showed that the value of effective stress and strain increased during turbulent flow, but still the location of the worst value of effective stress and strain is the same as the laminar flow. Tangential stress is not symmetrical in both laminar and turbulent flow regimes and it has most of its absolute value at the fin and in the flow front area. Also, in both flow regimes, the temperature distribution of the fin is two-dimensional which has caused asymmetric thermal strains and as a result asymmetric thermal stresses with significant values in the fin. According to the mentioned researches, it was clear that the effect of flow on the stresses created in annular fins bundle with eccentricity has not been studied so far. In this paper, an annular fin at fins bundle with eccentricity L= 1, 2, 3, 4, 5 mm is investigated to determine the effect of the eccentricity on the thermal stresses created in fins bundle and obtain the optimum eccentricity that creates the least thermal stress in the fins bundle. The effect of fin length and fin spacing on the best eccentricity which leads to the lowest amount of maximum thermal stress in the fin is investigated.

2. Problem Definition and Solution Method

Fig. (1a) and b show a two-dimensional view and a three-dimensional view of the annular fin by applying eccentricity, respectively. As shown in Fig. (1), a solution domain of a rectangular cube around the fin is considered to simulate the fluid environment in it. The distance of the center of the fin from the outlet of the flow (b=1.5m), from the inlet of the flow (a=0.7m), the height of the solution domain (h=0.004m), and the width of the solution domain (c=0.0408m) are considered. The problem is solved with a turbulent flow field and with constant properties by ANSYS Fluent software. The air enters the solution domain uniformly with V_{in} velocity and T_{in} temperature. The tube wall temperature is considered constant and equal to T_s.

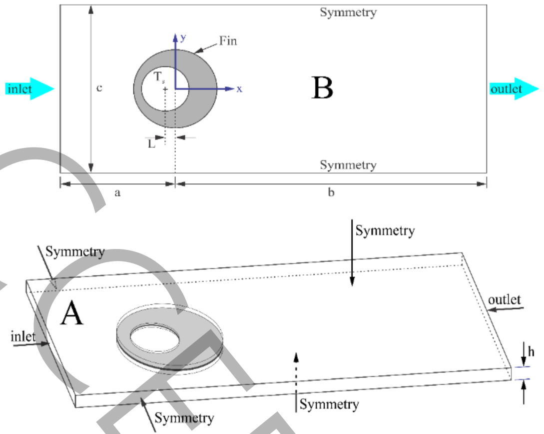


Figure 1. The view of the annular fin with eccentricity in the solution domain, B) top view of the annular fin with eccentricity in the solution domain

Heat and fluid flow equations of an incompressible and turbulent flow regime are express as continuity, momentum and energy equations:

$$\frac{\partial}{\partial x_i}(\rho u_i^f)=0 \tag{1}$$

$$\rho\frac{\partial}{\partial x_j}(u_i^f u_j^f)=-\frac{\partial p^f}{\partial x_j}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i^f}{\partial x_j}+\frac{\partial u_j^f}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_i^f}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_j}(-\overline{u_i'^f u_j'^f}) \tag{2}$$

$$-\overline{u_i'^f u_j'^f}=\mu_t\left(\frac{\partial u_i^f}{\partial x_j}+\frac{\partial u_j^f}{\partial x_i}\right)-\frac{2}{3}\left(\rho k+\mu_t\frac{\partial u_1^f}{\partial x_1}\right)\delta_{ij}$$

$$\frac{\partial}{\partial x_i}(u_i^f(\rho E+p^f))=\frac{\partial}{\partial x_i}\left[(k+k_t)\frac{\partial T^f}{\partial x_i}\right]$$

The governing equations of solid domain contain energy, equilibrium, and constitutive equations. Energy equation and boundary conditions are as below:

$$k^s\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T^s}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T^s}{\partial\theta^2}+\frac{\partial^2 T^s}{\partial z^2}\right)=\rho^s c_p{}^s\left(\frac{\partial T^s}{\partial t}\right) \tag{3a}$$

$$T^s(r,\theta,z,t)=T^s(r,\theta+2\pi,z,t),\ \frac{\partial T^s(r,\theta,z,t)}{r\partial\theta}=\frac{\partial T^s(r,\theta+2\pi,z,t)}{r\partial\theta},$$
$$T^s(r_b,\theta,z,t)=283.15k,\ k^s\frac{\partial T^s(r_e,\theta,z,t)}{\partial r}=k^f\frac{\partial T^f(r_e,\theta,z,t)}{\partial r} \tag{3b}$$

$$k^s\frac{\partial T^s(r,\theta,0,t)}{\partial z}=k^f\frac{\partial T^f(r,\theta,0,t)}{\partial z},$$
$$k^s\frac{\partial T^s(r,\theta,0.0005,t)}{\partial z}=k^f\frac{\partial T^f(r,\theta,0.0005,t)}{\partial z},\ T^s(r,\theta,z,0)=308.15k \tag{3c}$$

3. Results and Discussion

Figs. 2-3 show the maximum values of effective stress at different eccentricities for the fin at different heights of h_f=2, 4, 6, 8 mm in two fin spacing of 4 and 8 mm. According to Figs. 2a and 3a, for a fin with a height of h_f =8mm, it is observed that the maximum effective stress decreases until the eccentricity L = 3mm, and then with increasing eccentricity, the maximum effective stress increases.

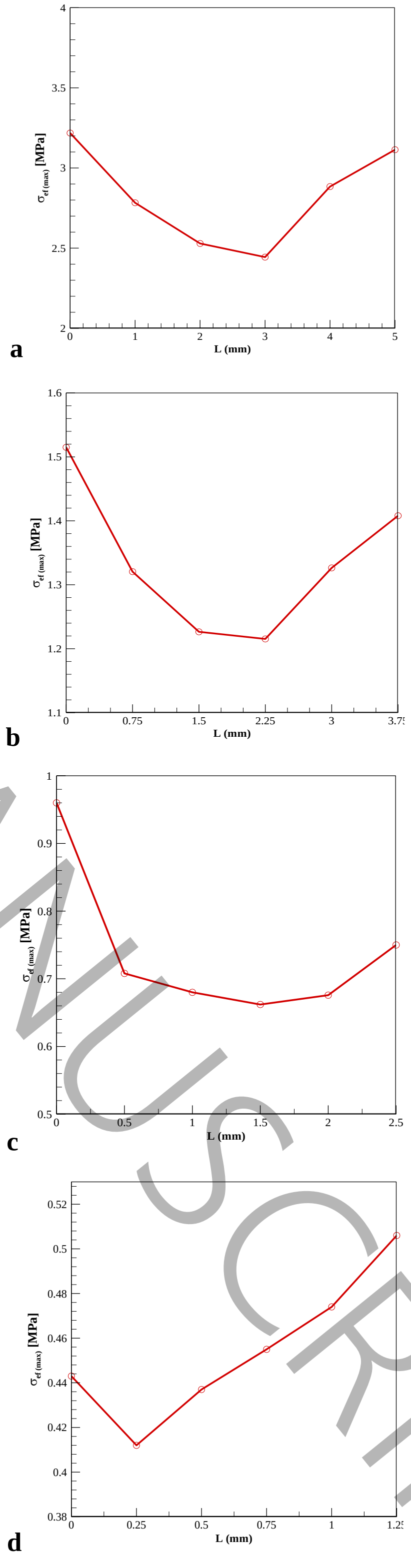
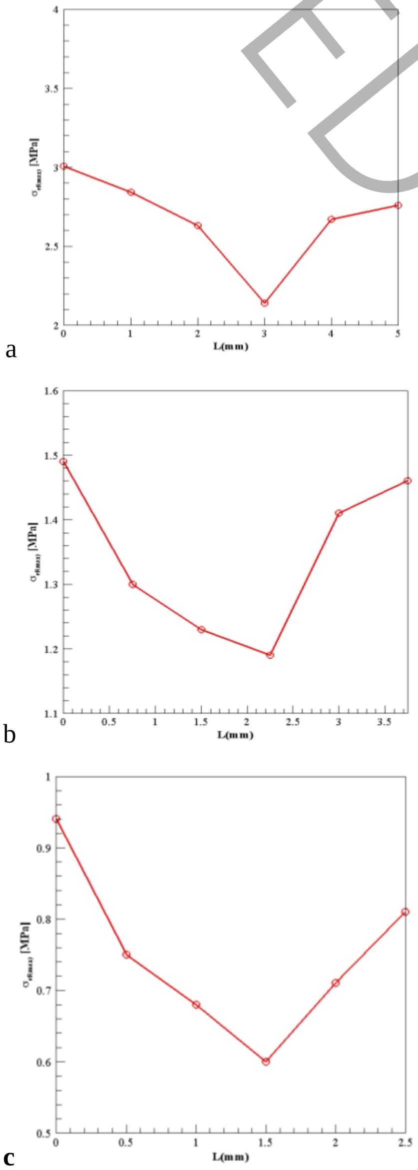


Fig2.The comparison of maximum effective stresses in various eccentricities with s=4mm

for a) h_f=8 mm b) h_f=6 mm c) h_f=4 mm d) h_f=2 mm

A similar decrease and increase behavior is observed for the fin with a height of h_f =6 mm, h_f =4mm, and h_f =2 mm according to Figs. 2 and 3 b-d. The optimal eccentricity is determined by comparing the maximum stresses relative to the non-eccentric fin in Figs. 2 and 3 in each mode. The results show that in fin spacing of 4 mm at a height of 8, 6, 4, and 2 mm, respectively, 24, 20, 30, and 6.76% reduction is observed compared to the non-eccentric state in each of the modes. The optimal eccentricities at heights of 8, 6, 4, and 2 mm are 3, 2.25, 1.5, and 0.25 mm, respectively. As can be seen, at a height of 2 mm, the effect of eccentricity is negligible because the resistance against conduction heat transfer is low and the heat distribution inside the fin is affected by the conductivity inside it rather than by the flow.



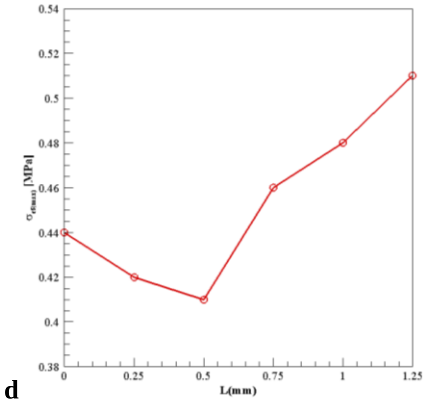


Fig3.The comparison of maximum effective stresses in various eccentricities with s=8mm for a) h_f=8 mm b) h_f=6 mm c) h_f=4 mm d) h_f=2 mm

4. Conclusions

Reduction of thermal stresses in a solid body is one of the needs of industries involved with tube and finned-tube exchangers. The results of the effect of eccentricity on thermal stresses showed that by creating eccentricity, the maximum effective stress created in the fin can be reduced. In the fin with a height of 8 mm to the eccentricity of 3 mm, the effective stress decreased and in the eccentricity larger than 3 mm again, the maximum effective stress increases. In the annular fin studied in this section, the fin with an eccentricity of 3 mm is optimal in terms of effective stress of the geometry and it has less effective maximum stress under the same conditions. Also, the eccentricity effect was studied for heights of 2, 4, and 6, and the optimal value was obtained for each of them.

5. References

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