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Characteristics of Straight Trapezoidal Cross-Sectional Fins under Unsteady Conditions

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Abstract

The aim of this research is to understand the characteristics of fins with a trapezoidal cross-section. The shape of the fin's cross-section is one of the influential factors affecting fin characteristics. In the design of fins, it is crucial to comprehend the characteristics of the fin as they relate to temperature distribution, heat transfer rate, and the efficiency of the fin. The research was conducted using numerical computation with an explicit finite difference method. Variations were made in the length of side 3 of the trapezium to 0 m, 0.02 m, and 0.04 m. The research results indicate that increasing the width of the fin enhances the temperature distribution, flow rate, and efficiency achievable by the fin. Significant improvement occurred when varying the side length from 0 m to 0.02 m, whereas subsequent variations did not considerably alter the efficiency. The highest efficiency achieved was 0.90 when the length of side 3 was 4 cm at the 300 seconds.

Keywords: Fin characteristics, finite difference method, unsteady state

1 Introduction

A working machine generates heat. If this generated heat is not dissipated, it can decrease the performance of the machine and even cause damage [1]. One way to reduce heat in a machine is by using fins. Fins serve to increase the rate of heat transfer from an object to the surrounding fluid. The heat transfer rate in fins is influenced by several factors such as the temperature difference between the fin surface and the fluid, the material of the fin, the geometry, and the cross-sectional area of the fin.[2–4]

In unsteady-state conditions, the temperature distribution in fins is influenced by the density (ρ), specific heat capacity (c), thermal conductivity (k), and thermal diffusivity (α) of the material composing the fin. Meanwhile, in steady-state conditions, only thermal conductivity significantly affects the temperature distribution. The convective heat transfer coefficient (h) is influenced by the properties of the fluid around the fin, fluid flow velocity, as well as the surface temperature of the fin and the temperature of the flowing fluid around it [5]. Moreover, higher fluid flow velocities result in larger values of the convective heat transfer coefficient (h). Temperature differences also play a role in determining these fluid properties. [6–9]

In its application, various forms of fins are utilized, and numerous studies on fins have been conducted employing different shapes such as capsule, cylinder, square, and triangle. Each fin shape possesses its distinct characteristics. The variation in fin geometry affects the fin's cross-sectional area, influencing temperature distribution and the rate of heat transfer from the fin [10–13]. In this study, temperature distribution calculations were obtained through numerical simulations using the explicit finite difference method. Understanding the temperature distribution and heat flow rate allows the efficiency of the fin to be computed. Efficiency, as one of the characteristics of a fin, is crucial to determine when designing a fin. Fin efficiency is the ratio between the actual heat released by the fin and the heat released if the entire fin surface had the same temperature as the fin base. This research aims to understand the characteristics of a trapezoidal cross-sectional fin under unsteady conditions, including (a) temperature distribution, (b) the rate of heat flow that the fin can release, and (c) fin efficiency.

2 Material and Methods

This research was conducted using computational methods employing an explicit finite difference approach. The fin was divided into 21 small elements known as control volumes. Each control volume has an equal distance of Δx, except for the control volumes located at the base and tip of the fin, which have a distance of $0.5\Delta x$. The fin has a trapezoidal cross-section with a varied length of side 3, as shown in Fig. 1.

The fin material is iron with a density of ρ = 7870 kg/m³, thermal conductivity k = 80.2 W/m°C, and specific heat capacity c = 447 J/kg°C. Iron is one of the natural materials widely used in alloys, for example in steel. Despite having lower strength compared to steel, iron has higher conductivity. The fin has an overall length of 0.05 m, a height of 0.02 m, and a distance between control volumes Δx = 0.0025 m. Side lengths 1 and 2 are 0.025 m and 0.015 m, respectively, while side length 3 is varied as 0 m, 0.02 m, and 0.04 m. The base temperature of the fin is considered constant at T_b = 100°C, and the surrounding fluid temperature is T_f = 30°C. The convective heat transfer coefficient is assumed constant at h = 50 W/m²°C.

The temperature distribution in each control volume is calculated using numerical equations derived from the principle of energy balance. There are three equations used to calculate the temperature distribution in the control volumes: at the base of the fin, between the base and the tip of the fin, and at the tip of the fin.

The temperature at the base control volume of the fin is maintained at T_b and remains unchanged over time, which can be expressed by equation (1).

$$T_i^{n+1} = T_1^{n+1} = T(0,t) = T_b \tag{1}$$

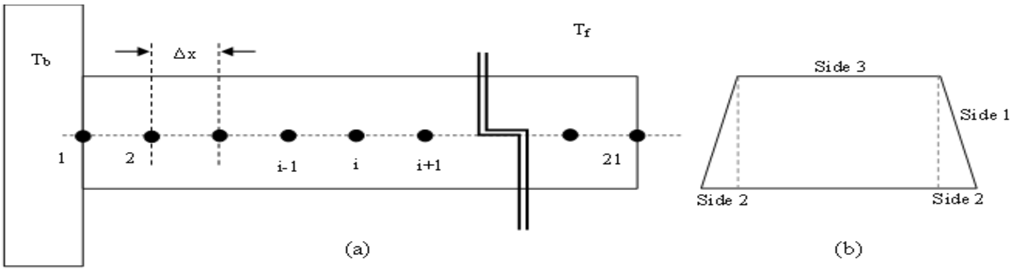


Figure 1. Straight fin with a trapezoidal cross-section, (a) side view, (b) front view

The temperature in the control volume between the base and the tip of the fin can be determined using equation (2). The temperature in the control volume at the tip of the fin is expressed by equation (3).

$$T_i = \frac{k\times\Delta x}{\rho\times c\times\Delta x^2}\left(T_{i-1}^n - T_i^n + T_{i+1}^n - T_i\right) + \left(\frac{h\times\Delta x}{k}\times\frac{A_{s,i}}{A_P}\times\left(T_f - T_i^n\right) + T_i^n\right) \tag{2}$$

$$T_i^{n+1} = \frac{k\times\Delta t}{0{,}5\times\rho\times c\times\Delta x^2}\left((T_{i-1}^n - T_i) + \left(\frac{h\times\Delta x}{k}(T_f - T_i^n)\right) + \left(\frac{h\times\Delta x}{k}\times\frac{A_{s,i}}{A_P}(T_f - T_i^n)\right) + T_i^n\right) \tag{3}$$

In unsteady-state conditions, the actual heat transfer rate ($q_{\mathrm{fin,actual}}$), the maximum heat transfer rate ($q_{\mathrm{fin,ideal}}$), and the heat transfer rate without fins (q_{nofin}) can be calculated successively using equations (4), (5), and (6).

$$q_{fin,actual}^{n+1} = h\,\sum_{i=1}^{m} A_s(T_i^{n+1} - T_f) \tag{4}$$

$$q_{fin,ideal}^{n+1} = h\,A_s(T_b - T_f) \tag{5}$$

$$q_{no\,fin}^{n+1} = h\,A_b(T_b - T_f) \tag{6}$$

The efficiency of the fin, which is the ratio between the actual heat released by the fin and the maximum heat that the fin can release, is calculated using equation (7).

$$\eta^{n+1} = \frac{q_{fin,\ actual}^{n+1}}{q_{fin,\ ideal}^{n+1}} \tag{7}$$

In equations (1)-(7):

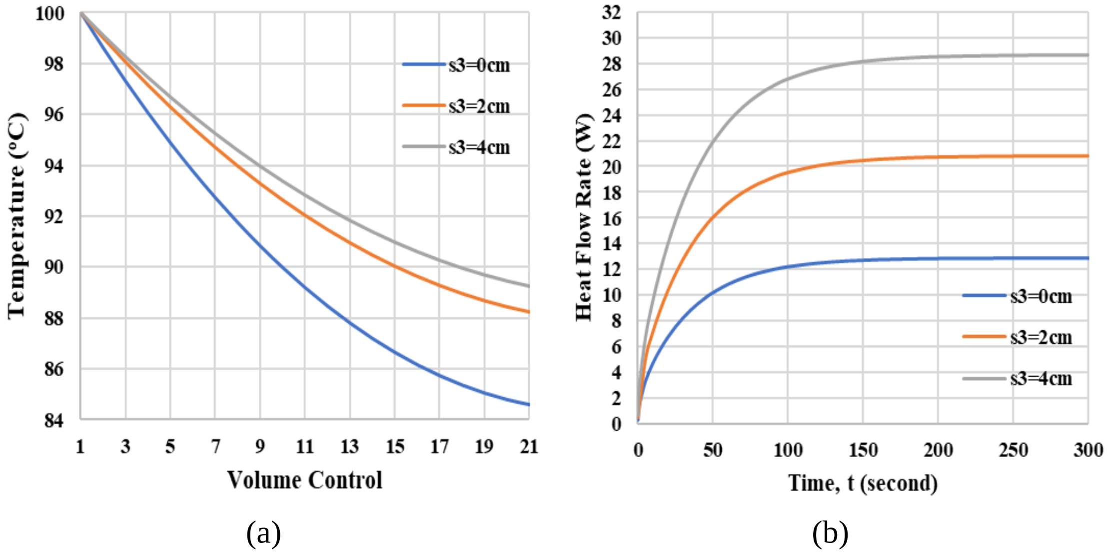
T_i^{n+1} : The temperature at the i position, in the n+1 iteration (^{o}C)
T_i^n : The temperature at the I position, in the n+1 iteration (^{o}C)
T_{i-1}^n : The temperature at the i-1 position, in the n iteration (^{o}C)
T_{i+1}^n : The temperature at the i+1 position, in the n iteration (^{o}C)
T_f : Fluid temperature around the fin (^{o}C)
Δt : Time step, from the n to the n+1 iteration (s)
Δx : Distance between control volumes (m)
$A_{s,i}$: Area of the surface of the control volume at the i position touching the fluids around the fin (m^2)
A_P : Area of the cross section of the fin (m^2)
ρ : The density of the fin material (kg/m^3)
c : Specific heat of the fin material (J/kg^{o}C)
k : Thermal conductivity (W/m°C)

h : Convection heat transfer coefficient (W/m^2°C)

3 Results and Discussions

The results of temperature distribution, heat transfer rate, and fin efficiency can be observed in Fig. 2. In unsteady-state conditions, the temperature distribution continues to change over time. In this study, because T_b is maintained at a constant temperature of 100°C, higher than the surrounding fluid, the temperature at each control volume will continue to increase until reaching a steady state throughout the control volumes. In Fig. 2, the temperature distribution is examined at the 300 seconds by comparing the temperature of each control volume for various fin cross-sectional width variations or lengths of side 3. Heat transfer rates and efficiency are evaluated at each time unit for various fin cross-sectional width variations.

In Fig. 2(a), it is evident that increasing the length of side 3 of the trapezium enhances the temperature distribution within the fin. Heat from the base of the fin is transferred more rapidly and extensively towards the fin's end, specifically at control volume 21. The difference in temperature distribution between variations of side 3 at 2 cm and 4 cm is smaller compared to having a length of 0 cm or no side 3. At the 300 seconds, nearing a steady state, the temperature at the end of the fin for the 4 cm variation reaches 89.3°C, the 2 cm variation reaches 88.2°C, and the 0 cm variation reaches 84.5°C. Fig. 2(b) demonstrates that over time, the heat transfer rate increases until reaching a certain point before leveling off. The heat transfer rate is proportional to the rise in temperature at each control volume. The substantial difference between the fin's temperature and the surrounding fluid amplifies the heat transfer rate. The 4 cm variation exhibits the highest heat transfer rate at 300 seconds, measuring 28.6 W, followed by the 2 cm variation at 20.9 W, and finally, the 0 cm variation at 12.9 W. Fig. 3, displays the efficiency of the three fin variations. The fin efficiency increases proportionally with the larger temperature difference between the fin's control volume and the surrounding fluid.



(a) (b)

Figure 2. (a) Temperature distribution, t = 300 seconds, (b) Heat transfer rate

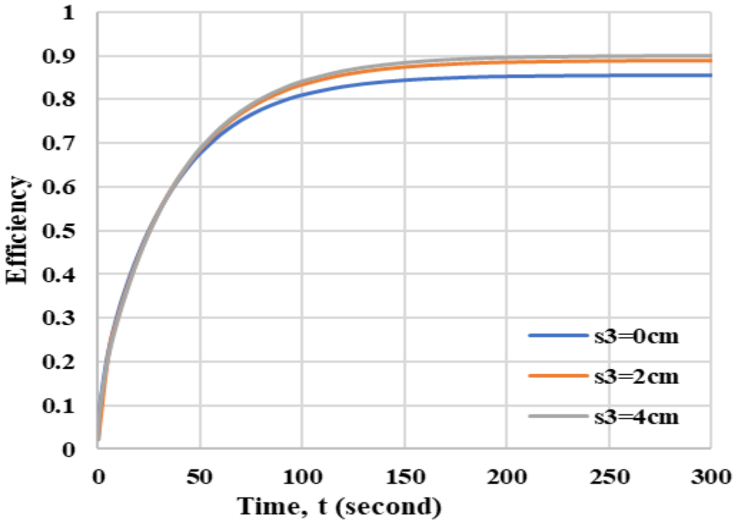


Figure 3. Fin efficiency

The 4 cm and 2 cm variations have closely similar efficiency graphs, indicating that increasing the length of side 3 beyond 2 cm doesn't yield a significant improvement in efficiency compared to having no side 3, or the 0 cm variation. The highest efficiency achievable by the trapezoidal fin with a 4 cm side 3 is 0.90, which is not significantly different from the 2 cm variation, reaching a maximum efficiency of 0.89, while the 0 cm variation or without side 3 attains a maximum efficiency of 0.85.

4 Conclusions

From the research findings, it can be concluded that the width variation in trapezoidal-shaped fins influences the fin's characteristics. Increasing the fin width enhances the temperature distribution, heat transfer rate, and efficiency achievable by the fin. Significant improvements occur when transitioning from a side length variation of 0 cm to 2 cm, while subsequent variations show little change in efficiency. The highest achievable efficiency is 0.90 at a side length variation of 4 cm at the 300 seconds.

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