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# ROLE OF RANDOM ROUGHNESS ON THERMAL PERFORMANCE OF MICRO-FINS

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**Abstract**

Heat transfer in rough circular cylinder microfins is studied and a novel analytical model is developed. Surface roughness is assumed to posses a Gaussian isotropic distribution. It is shown that, as a result of roughness, both cross-sectional and surface areas are increased. As a result, an enhancement is observed in the heat transfer rate and thus the thermal performance of microfins. The present model can be implemented to analyze other geometries such as rectangular and tapered microfins.

**Nomenclature**

| | | |
|---|---|---|
| $A_c$ | = | cross-sectional area, $m^2$ |
| $A_s$ | = | surface area, $m^2$ |
| $a$ | = | mean radius of rough microfin, $m$ |
| $D$ | = | microfin diameter, $m$ |
| $h$ | = | convection heat transfer coefficient, $W/m^2K$ |
| $k$ | = | fin thermal conductivity, $W/mK$ |
| $k_f$ | = | fluid thermal conductivity, $W/mK$ |
| $L$ | = | microfin length, $m$ |
| $m_s$ | = | mean absolute surface slope, $[-]$ |
| $Nu_D$ | = | Nusselt number based on diameter, $[-]$ |
| $Q$ | = | heat flow rate, $W$ |
| $q$ | = | heat flux, $W/m^2$ |
| $R_f$ | = | fin thermal resistance, $K/W$ |
| $r$ | = | microfin radius, $m$ |
| $T$ | = | temperature, $K$ |

***Greek***

| | | |
|---|---|---|
| $\epsilon$ | = | relative roughness, $\sigma/a$ |
| $\zeta$ | = | non-dimensional length, $x/L$ |
| $\theta$ | = | non-dimensional temperature |
| $\sigma$ | = | roughness standard deviation, $m$ |
| $d\Lambda$ | = | length of surface element, $m$ |

***Subscripts***

| | | |
|---|---|---|
| $0$ | = | reference value, base, smooth microfin |
| $\theta$ | = | in angular direction |
| $x$ | = | in longitudinal direction |
| $\infty$ | = | ambient |

## 1 INTRODUCTION

Thermal phenomena play a key role in a variety of applications in Micro Electro Mechanical Systems (MEMS) such as thermal actuators in RF devices [1], thermal flexture actuators [2], and thermal-compliant microactuators [3]. Recently, micro pin fin heat exchangers have been utilized in advanced thermal management solutions ranging from gas turbine blades cooling [4] to microelectronic chip cooling [5].

According to Brown [6], there are several MEMS fabrication techniques currently in widespread use, including bulk micromachining, surface micromachining, fusion bonding, and LIGA, which is a composite fabrication procedure of lithography, electroforming, and molding. The polycrystalline silicon substrates used in micromechanical devices are often rough. Moreover, Atomic Force Microscopy (AFM) images revealed that the surfaces manufactured by

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MEMS technologies have roughness [7]. The level of this surface roughness depends extensively on the fabrication process used and material properties. As the dimensions of micro structures decrease, the importance of surface roughness becomes more significant. This surface roughness can be envisioned as another extended surface on the original extended surface, i.e., *fins on fins*.

The heat transfer augmentation due to the presence of surface roughness has been experimentally investigated by several researchers. Achenbach [8] showed through experiments that the heat transfer from a circular cylinder to the cross-flow of air increases as a result of surface roughness. He used knurling to created artificial roughness on the cylinders studied. Wang et al. [9] experimentally studied natural convection in air over a uniformly heated, vertical surface covered with micro-grooved films. V-grooves with depths of 18 to 150 $\mu m$ were used. The data of [9] showed that natural convection was enhanced by up to 20% when micro-grooves were used. Honda and Wei [5] conducted experiments and studied the effect of roughness on micro pin fins on the boiling heat transfer from a silicon chip immersed in a pool of FC-72. Square pin fins of dimensions $50 \times 50 \times 60$ $\mu m^3$ with roughness in the order of 25 to 32 $nm$ were used. They reported that the pin fin with higher roughness showed a higher thermal performance.

As reviewed briefly, existing experimental studies point out an increase in thermal performance when surface roughness exists. However, to the authors' knowledge, there are no analytical models in the literature that predicts this empirically observed trend. In this paper, an analytical model is developed that takes into account the effect of roughness on the thermal performance of a circular cylinder microfin. The term *roughness* has been used to refer to a variety of surface treating/irregularities in the thermal-fluid literature, e.g. knurling and V-grooves. However, in this study, we focus only on *random isotropic* (Gaussian) roughness which can be thought of as surface deviations from its nominal topography. The present model can be implemented, following the same procedure, to rectangular and other micro structures geometries. The results of the analysis can be used to improve upon the thermal analysis and design of microfins and micro structures.

## 2 HEAT TRANSFER FROM EXTENDED SURFACES

The term extended surface or fin is commonly used to refer to a solid that experiences energy transfer by conduction within its boundaries, as well as energy transfer by convection between its boundaries and the surroundings. Consider the extended surface of Fig. 1. The following assumptions are made:

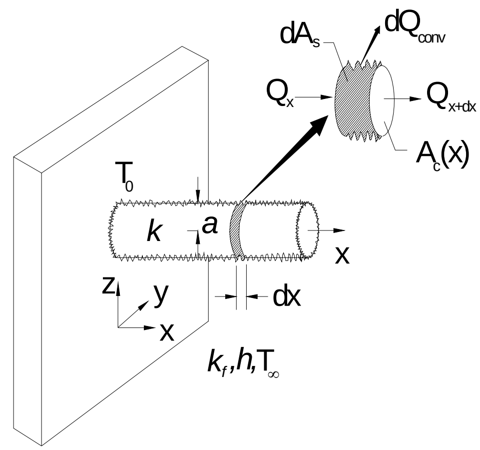


Figure 1. ENERGY BALANCE FOR AN EXTENDED ROUGH SURFACE

- heat conduction is one dimensional, i.e. in the longitudinal $x$ direction
- surface is rough with an isotropic Gaussian distribution of heights
- negligible radiation from the surface
- uniform heat transfer coefficient, $h$
- constant solid thermal conductivity including surface asperities, $k$
- steady-state conditions.

Applying conservation of energy to the differential element shown in Fig. 1, one obtains [10]

$$\frac{d^2T}{dx^2} + \frac{1}{A_c}\frac{dA_c}{dx}\frac{dT}{dx} - \frac{1}{A_c}\frac{h}{k}\frac{dA_s}{dx}(T - T_\infty) = 0 \qquad (1)$$

where Eq. (1) provides a general form of the energy balance for one-dimensional steady-state heat flow in an extended surface. A source term can also be considered in Eq. (1).

It should be noted that the thermal conductivity of the structure is assumed to be isotropic, which means the same thermal conductivity for bulk and asperities. For small RMS roughness, this assumption is safe. However, for larger values of surface roughness, thermal conductivity values near the surface may be noticebaly degraded, depending upon the material and the fabrication process.

The terms $A_c$, $dA_c/dx$, and $dA_s/dx$ in Eq. (1) are functions of surface roughness.

## 3 SURFACE ROUGHNESS

According to Liu et al. [11] five types of instruments are currently available for measuring the surface topography: i) stylus-type surface profilometer, ii) optical (white-light

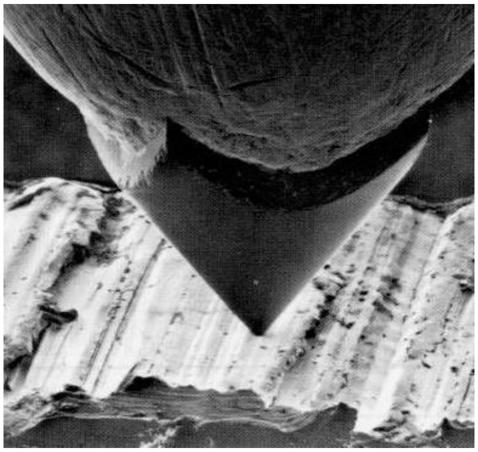

Figure 2. ROUGHNESS MEASUREMENT: STYLUS PROFILOMETER[4]

interference) measurements, iii) Scanning Electron Microscope (SEM), iv) Atomic Force Microscope (AFM), and v) Scanning Tunneling Microscope (STM). Surface texture is most commonly measured by a profilometer, which draws a stylus over a sample length of the surface, see Fig. 2 [4]. A datum or centerline is established by finding the straight line, or circular arc in the case of round components, from which the mean square deviation is a minimum. When the surface is Gaussian, the standard deviation $\sigma$ is identical to the RMS value [12], $R_q$.

$$\sigma = R_q = \sqrt{\frac{1}{l}\int_0^l z^2\left(x\right)dx} \tag{2}$$

where $l$ is the sampling length in the $x$ direction and $z$ is the measured value of the surface heights along this length. The absolute average surface slopes, $m_s$, can be determined across the sampling length from the following:

$$m_s = \frac{1}{l}\int_0^l \left|\frac{dz\left(x\right)}{dx}\right| dx \tag{3}$$

## 4 ROUGH MICRO PIN FINS

Consider a rough micro pin fin with the mean radius of $a$ and length $L$, Figs. 3 and 4. As shown schematically in the figures, roughness of the fin is assumed to posses a Gaussian distribution in both angular and longitudinal directions. It must be noted that the surface slopes of asperities, $m_s$, is exaggerated. In reality, the surface asperities can be visualized as shallow hills and valleys.

[4]Fig. from: Mark C. Malburg, "Cylinder Bore Surface Texture Analysis," Digital Metrology Solutions, Inc., 2002.

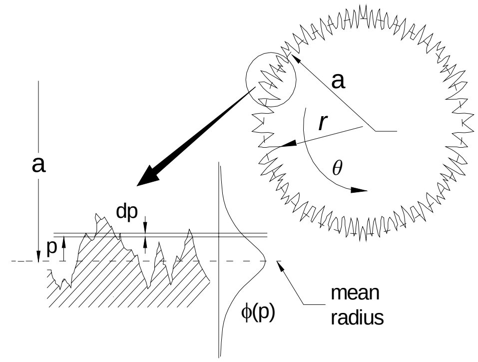


Figure 3. CROSS-SECTION OF ROUGH PIN FIN: GAUSSIAN ROUGHNESS

Owing to the random nature of roughness, an exact value of the local radius, $r$, can not be used to specify the radius of rough microfins. Instead, probabilities of different radii occurring should be computed. A random variable, $p$, is used to represent the deviations of the local radius, $r$, in the angular direction, Fig. 3. The standard deviation of $p$ is the surface roughness $\sigma_\theta$ and has the following Gaussian distribution:

$$\phi\left(p\right) = \frac{1}{\sqrt{2\pi}\sigma_\theta}\exp\left(-\frac{p^2}{2\ \sigma_\theta^2}\right) \tag{4}$$

The local radius can vary over a wide range of values from much larger to much smaller radii than the mean radius $a$, valleys and hills in the figure, with the Gaussian probability distribution shown in Eq. (4).

The fin surface also has roughness in the longitudinal direction $x$, see Fig. 4. The variations of the local radius of the microfin, $r$, in the longitudinal direction is shown by another random variable, $q$, with the same Gaussian distribution as in the angular direction.

$$\phi\left(q\right) = \frac{1}{\sqrt{2\pi}\sigma_x}\exp\left(-\frac{q^2}{2\ \sigma_x^2}\right) \tag{5}$$

The local radius of the microfin can be written as

$$r = a + p + q \tag{6}$$

where $a$ is the mean statistical value of the local radius, $r$, over the cross-sections over the entire length, $L$, of the microfin.

To better understand Eq. (6), consider cross-sections of a rough microfin at different longitudinal locations, Fig. 4. These cross-sections can have different mean radii where the probability of these radii occurring can be determined from Eq. (5), $a + q$. Meanwhile, the actual radius at each

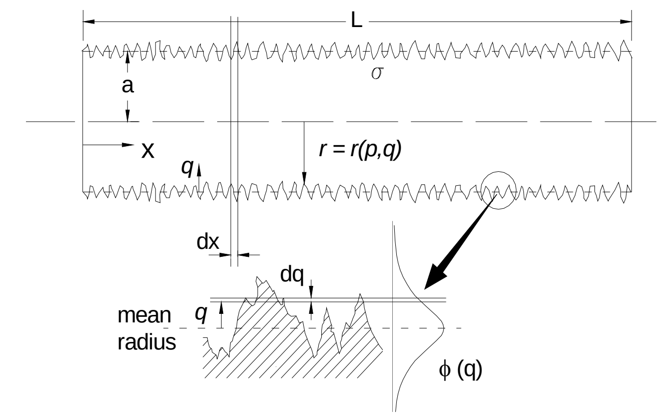


Figure 4. LONGITUDINAL CROSS-SECTION OF RANDOM ROUGH PIN FIN

cross-section varies around the mean radius, $a + q$, in the angular direction (variations of $p$) with the probability distribution described in Eq. (4). Therefore, the local radius of a microfin, $r$, is a function of both random variables $p$ and $q$, i.e., $r = r(p, q)$. We assume that the local radius is the superposition of the two random variables, as shown in Eq. (6). Note that the variables $p$ and $q$ are independent. For argument sake, consider an imaginary case where a microfin has roughness only in the angular direction; thus one can write, $r = r(p)$. As a result, an average of these variables $[r = a + (p + q)/2]$ does not provide a correct answer.

In general case, the standard deviations $\sigma_\theta$ and $\sigma_x$ can be different; however in this study, we assume an isotropic roughness; thus, $\sigma_\theta = \sigma_x = \sigma$.

### 4.1 Cross-Sectional Area, $A_c$

The cross-sectional area of a circular cylinder micro pin fin can be calculated from, $A_c = \pi r^2$; using Eq. (6), it can be written

$$A_c = \pi \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} (a + p + q)^2 \, \phi(p) \, \phi(q) \, dp \, dq \tag{7}$$

Equation (7) considers the probabilities of all values of radius, $r$, occurring according to the Gaussian distribution. It should be noted that it is mathematically possible for the variables $p$ and $q$ to have values ranging from $-\infty$ to $+\infty$, see Eqs. (4) and (5). However, the probability of occurring much larger/ smaller radii than the mean radius, $a$, are quite small.

After change of variables and simplifying, Eq. (7) becomes

$$A_c^* = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} (1 + \epsilon u + \epsilon v)^2 \, e^{-u^2/2} e^{-v^2/2} du \, dv \tag{8}$$

where $A_c^* = A_c / A_{c,0}$, $A_{c,0} = \pi a^2$, and $\epsilon$ are the normalized cross-sectional area, cross-sectional area of the smooth microfin, and the relative surface roughness, respectively.

$$\epsilon = \frac{\sigma}{a} \tag{9}$$

Note that the relative roughness, $\epsilon$, is defined as the RMS surface roughness over the *radius* of the fin. Equation (8) calculates an *effective* cross-sectional area for rough pin fin. After solving the integral, one finds

$$A_c^* = \frac{A_c}{A_{c,0}} = 1 + 2\epsilon^2 \tag{10}$$

As expected, the effect of surface roughness is to increase the cross-sectional area of a rough fin. Notice that at the limit where roughness goes to zero $\epsilon \to 0$ (smooth surface), $A_c^* \to 1$.

### 4.2 Surface Area, $A_s$

The differential lateral surface area of a rough micro pin fin can be found from

$$dA_s = r d\theta d\Lambda \tag{11}$$

where $r = r(x, \theta)$ and $d\Lambda$ is the statistical mean length of the rough surface element that can be found from

$$d\Lambda = \int_x^{x+dx} \sqrt{1 + \left(\frac{dr}{dx}\right)^2} dx \tag{12}$$

It is assumed that the mean absolute surface slope, $m_s$ see Eq. (3), can be used to estimate the statistical mean length of the surface $d\Lambda$, i.e.,

$$m_s \simeq \frac{dr}{dx} \tag{13}$$

This assumption may have some degree of inaccuracies and may need modification when compared against experimental data. However, the surface slope $m_s$, based on its definition, is a representative averaged value for the slope and is constant for a surface. In addition, this assumption is consistent with Eq. (1) since the energy balance is for the entire micro pin fin. Thus, one may write

$$dA_s = 2\pi r \sqrt{1 + m_s^2} \, dx \tag{14}$$

Averaging Eq. (14) over the microfin length, the mean value of $r$ must be replaced by $a$ and the effective mean lateral surface area of a rough micro pin fin will be

$$A_s = 2\pi a L\sqrt{1+m_s^2} \tag{15}$$

with $A_{s,0} = 2\pi a L$,

$$A_s^* = \frac{A_s}{A_{s,0}} = \sqrt{1+m_s^2}$$

Using the same method, one can find $dA_c/dx$

$$\frac{dA_c}{dx} = 2\pi r\frac{dr}{dx} \tag{16}$$

which can be averaged over the microfin and written as

$$\frac{dA_c}{dx} = 2\pi a m_s \tag{17}$$

Substituting Eqs. (10), (14), and (17) in Eq. (1), one finds

$$\frac{d^2T}{dx^2} + \frac{2m_s}{a\left(1+2\epsilon^2\right)}\frac{dT}{dx} - \frac{h}{k}\frac{2\sqrt{1+m_s^2}}{a\left(1+2\epsilon^2\right)}\left(T-T_\infty\right) = 0 \tag{18}$$

This ODE can be non-dimensionalized in the following form

$$\frac{d^2\theta}{d\zeta^2} + \alpha\frac{d\theta}{d\zeta} - \beta\theta = 0 \tag{19}$$

where $\theta = \left(T-T_\infty\right)/\left(T_0-T_\infty\right)$ and $\zeta = x/L$, and

$$\alpha = \frac{2m_s}{\left(1+2\epsilon^2\right)}\left(\frac{L}{a}\right) \qquad \beta = \frac{2hL^2\sqrt{1+m_s^2}}{ka\left(1+2\epsilon^2\right)} \tag{20}$$

The non-dimensional parameter $\beta$ can be written in terms of Nusselt number as follows:

$$\beta = Nu_D\left(\frac{k_f}{k}\right)\left(\frac{L}{a}\right)^2\frac{\sqrt{1+m_s^2}}{1+2\epsilon^2} \tag{21}$$

where $Nu_D = hD/k_f$, $D = 2a$, and $k_f$ are the Nusselt number, diameter of microfin, and the fluid thermal conductivity, respectively.

To solve Eq. (19), the following boundary conditions are used

$$\theta = 1 \quad \text{at} \quad \zeta = 0 \qquad \frac{d\theta}{d\zeta} = 0 \quad \text{at} \quad \zeta = 1 \tag{22}$$

The analytical solution of Eq. (19) with the boundary conditions described in Eq. (22) is

$$\theta\left(\zeta\right) = e^{-\alpha\zeta/2}\left[c_1\sinh\left(\gamma\zeta\right) + c_2\cosh\left(\gamma\zeta\right)\right] \tag{23}$$

where $c_2 = 1$ and

$$c_1 = \frac{\alpha\cosh\left(\gamma\right) - 2\gamma\sinh\left(\gamma\right)}{-\alpha\sinh\left(\gamma\right) + 2\gamma\cosh\left(\gamma\right)} \quad \text{and} \quad \gamma = \frac{\sqrt{\alpha^2+4\beta}}{2} \tag{24}$$

Heat flux at the base of the fin can be found from

$$q_{base} = -k\frac{T_0-T_\infty}{L}\left.\frac{d\theta}{d\zeta}\right|_{\zeta=0} \tag{25}$$

Using Eq. (23), one can find

$$\left.\frac{d\theta}{d\zeta}\right|_{\zeta=0} = \gamma c_1 - \frac{\alpha}{2} \tag{26}$$

The mean temperature of a fin can be calculated from

$$\theta_{ave} = \int_0^1 \theta\left(\zeta\right)d\zeta \tag{27}$$

Substituting temperature profile $\theta\left(\zeta\right)$ in Eq. (27), after integrating and simplifying, one finds

$$\theta_{ave} = \frac{4c_1\gamma + 2\alpha}{\alpha^2 - 4\gamma^2} - \left\{\frac{c_1+1}{\alpha-2\gamma}e^{\gamma} + \frac{c_1-1}{\alpha+2\gamma}e^{-\gamma}\right\}e^{-\alpha/2} \tag{28}$$

Thermal performance of a microfin can be expressed in terms of performance, or efficiency, and or thermal resistance. In this paper, thermal resistance is chosen because of its convenience when used in a thermal resistance network analysis. Considering the difference between the base and the fluid temperature as the deriving potential, a fin resistance, $R_f$, is defined as

$$R_f = \frac{T_0 - T_\infty}{Q_f} \tag{29}$$

Fin resistance becomes:

$$R_f = \frac{L}{kA_c\left(\alpha/2 - \gamma c_1\right)} \tag{30}$$

## 5 PARAMETRIC STUDY

A parametric study is performed to investigate the effect of surface roughness on different aspects of thermal performance of micro pin fins. A typical (arbitrary) micro pin fin is selected for the study, the input parameters are shown in the plots. To better demonstrate the effect of roughness, some of the studied parameters are non-dimensionalized with respect to their smooth values, i.e., $\sigma = 0$.

The effect of surface roughness on temperature profile of a micro pin fin is shown in Fig. 5. The solution is found using Eq. (23). The surface slope, $m_s$, may be estimated

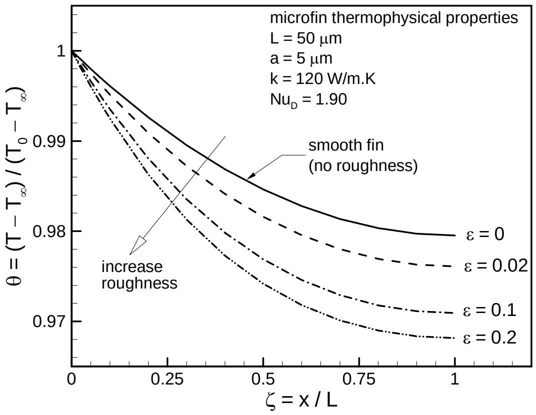


Figure 5. EFFECT OF SURACE ROUGHNESS ON TEMPERATURE PROFILE OF PIN FIN

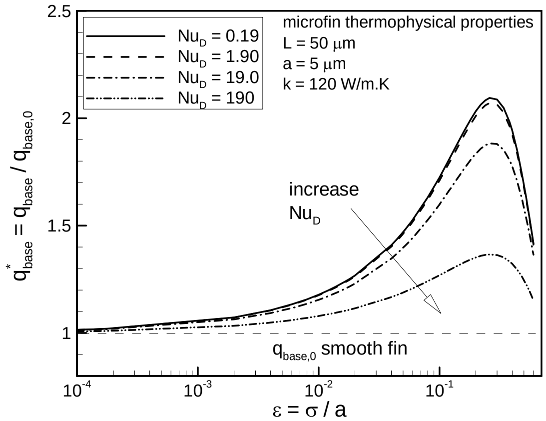


Figure 6. EFFECT OF ROUGHNESS ON BASE HEAT FLUX OF PIN FIN AT DIFFERENT $Nu_D$

using an empirical relationship suggested by Lambert and Fletcher [13]

$$m_s = 0.076\sigma^{0.52} \tag{31}$$

where $\sigma$ is the surface RMS roughness in micron. The uncertainty of the above correlations is high and use of this correlation is justifiable only where the surface slope is not reported and/or an approximate estimation of $m_s$ is needed [14]. A family of curves are shown in Fig. 5, each corresponding to a relative roughness value in the range of $0 \leq \epsilon \leq 0.2$, while all other input parameters are kept constant. As shown, the microfin temperature decreases as roughness increases.

The effect of roughness on micro pin fin heat flux is shown in Fig. 6. By adding roughness, the fin heat flux increases in microfins. The solution predicts an optimum relative roughness for a microfin which maximizes the fin heat flux. As roughness increases, the cross-sectional area $A_c$ and surface area $A_s$ both increase according to Eqs. (10) and (15), respectively. These enhancements lead to a higher microfin heat flux. However, the increase in cross-sectional area $A_c$ is larger than the increase in $A_s$. Therefore, more heat is being conducted into the fin but the increase in the surface area is not as high to dissipate this heat to the surroundings. It must be noted that this phenomenon is predicted at a large value of relative roughness for the studied microfin, i.e. $\epsilon \approx 0.2$ which is not expected to occur in real application. The optimum surface roughness for a rough micro pin fin can be found from

$$\frac{dq_{base}}{d\epsilon} = \frac{d}{d\epsilon}\left(\gamma c_1 - \frac{\alpha}{2}\right) = 0 \tag{32}$$

where $\alpha$, $\gamma$, and $c_1$ are functions of roughness and are given in Eqs. (20) and (24).

Figure 6 also shows the effect of $Nu_D$ on the non-dimensional fin heat flux as a family of curves. It should be noted that the absolute value of fin heat flux increases as Nusselt number increases; but in Fig. 6 fin heat fluxes are normalized with respect to their smooth values. As $Nu_D$ increases, the rate of increase in fin heat flux decreases (curves are flattened). In other words, the rate of increase in fin heat flux due to roughness is more significant at lower values of $Nu_D$, i.e., natural convection.

Another important parameter is the ratio of length or radius, $L/a$, which appears in both $\alpha$ and $\beta$. Figure 7 demonstrates the effect of $L/a$ on the non-dimensional base heat flux of a micro pin fin as relative roughness is varied while other parameters are kept constant. To keep Nusselt number constant, the radius of the microfin is kept constant and the length is varied. It should be noted that the absolute value of fin heat flux increases as $L/a$ (length of microfin) increases; but in Fig. 7 fin heat fluxes are normalized with respect to their smooth values. It is interesting to observe that the rate of increase due to roughness increases as the microfin length increases to a certain value of $L/a$ and then decreases by further increase in $L/a$. Therefore, it can be concluded that an optimum value of $L/a$ (length) for a microfin can be found that maximizes the enhancement in fin heat flux due to roughness.

The effect of roughness on the mean temperature, $\theta_{ave}$, and thermal resistance, $R_f$, of a micro pin fin, see Eq. (28), are shown in Figs. 8 and 9. As shown the thermal resistance and the mean temperature decrease as roughness is introduced to the microfin.

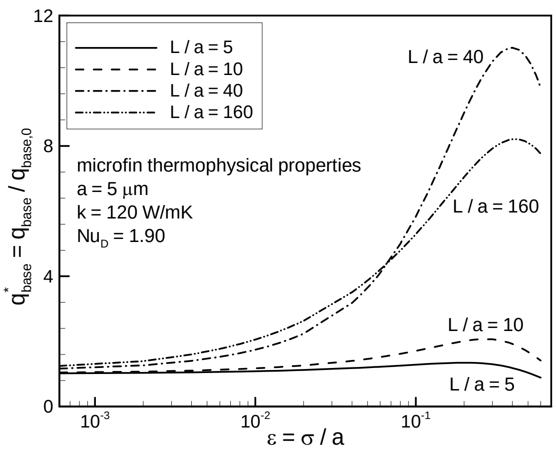


Figure 7. EFFECT OF ROUGHNESS ON BASE HEAT FLUX OF PIN FIN AT DIFFERENT VALUES OF L/a

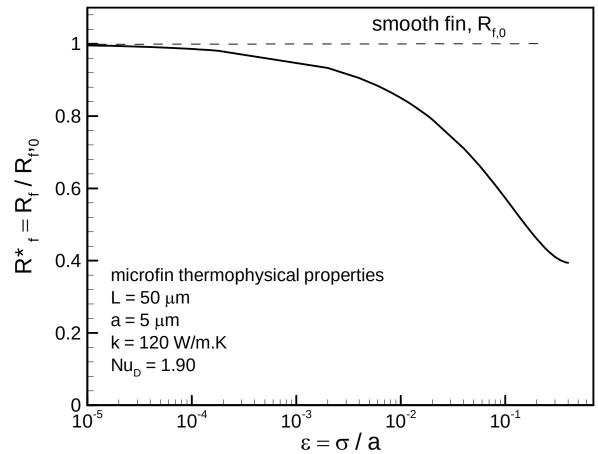


Figure 9. EFFECT OF ROUGHNESS ON FIN THERMAL RESISTANCE

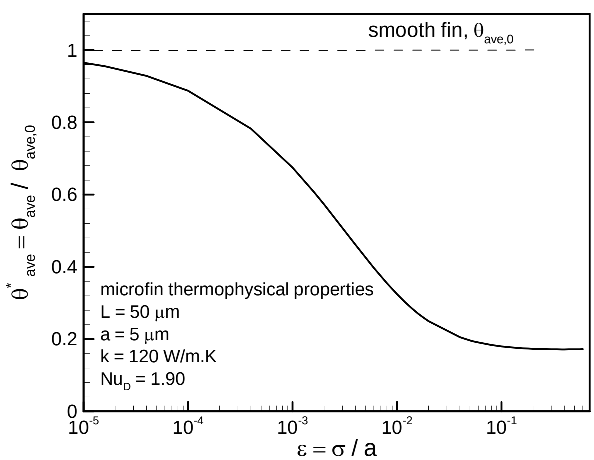


Figure 8. EFFECT OF SURACE ROUGHNESS ON AVERAGE TEMPERATURE OF PIN FIN

## 6 SUMMARY AND CONCLUSIONS

The effect of random, isotropic surface roughness on microfins is studied and a novel analytical model is developed. The results for circular cylinder micro pin fins are presented; however, the proposed model can be implemented to other geometries such as rectangular and tapered microfins. As a result of advances in fabrication techniques of MEMS, many processing techniques can be utilized to fabricate periodic surfaces. The model can be extended to predict the thermal performance of periodic surfaces with or without roughness.

Two independent random variables are considered to account for deviations of the local radius of rough microfins in the angular and longitudinal directions. The local radius is assumed to be the superposition of the two random variables. Relationships are derived for the temperature distribution, heat flux, thermal resistance, and mean temperature of circular cylinder rough micro pin fins.

It is shown that, as a result of roughness, both cross-sectional and surface area of microfins are increased which result in an enhancement in the heat transfer rate and thus the thermal performance of microfins. Moreover, it is observed that as the surface roughness increases the mean temperature and thermal resistance of microfin decrease. The following are found, through analysis,

- an optimum surface roughness exists that maximizes the fin heat flux
- the rate of increase in microfin heat flux due to roughness is higher at lower Nusselt numbers; thus, better improvement in thermal efficiency of a microfin (due to roughness) can be achieved when approaching natural convection
- an optimum length (or $L/a$) for a microfin can be found in order to maximize the thermal performance of a microfin.

No experimental data can be found in the literature to verify the model. Therefore, experimental investigation is recommended to validate the present model. However, it should be mentioned that designing and conducting such experiments is a great challenge due to the small size of microfins. Furthur, roughness measurements, in particular determining the surface slope $m_s$, can be a difficult task.

## ACKNOWLEDGMENT

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