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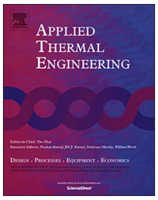

Thermal effectiveness and mass usage of horizontal micro-fins under natural convection

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HIGHLIGHTS

- Individual and overall effectivenesses up to 3.3 and 1.1 are respectively found.
- The individual effectiveness increases by reducing the thickness to spacing ratio.
- Micro-fins can enhance the mass specific heat transfer coefficient up to 50%.
- The mass specific heat transfer coefficient increases with height and spacing.
- The correlations are found to be consistent for upward and downward orientations.

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ABSTRACT

In recent times, the micro-technologies have gained prominence in various engineering applications. The micro-technologies are already in use for cooling purposes in several systems, but the information on the thermal performance of micro-fins under natural convective heat transfer conditions is yet limited. The correlations between heat transfer coefficients and fin geometry have already been investigated, but are not sufficient to optimize the design of the micro-finned arrays. For this reason, the present investigation gives an overview of micro-fins behavior taking into account, for the first time, different heat sink metrics: the fin effectiveness and the mass specific heat transfer coefficient. The results of an original experimental investigation are merged with the data available in literature. Natural convective micro-fins are able to achieve overall fin effectivenesses higher than 1.1. Even if not always beneficial in terms of heat transfer, micro-fins are found always positive in terms of the material usage. In this light, micro-fins can be considered advantageous in those applications that require a minimized weight of the heat sinks. Moreover, a limited effect due to the orientation is observed.

1. Introduction

Extended surfaces/fins are commonly used to enhance the heat transfer from a system to the surrounding fluid. The application of fins has been investigated in numerous studies and is currently employed for many different purposes, such as electronics, industrial processes and energy generation. Fins in natural convection are considered as passive coolers, since they do not require input of mechanical or electrical power. Fins act by exploiting both the natural convective motion of a fluid due to a thermal gradient and the radiative heat transfer [1]. Passive coolers are generally considered more reliable and less exposed to cooling failures [2] than active coolers, which need instead external energy in input to perform.

Industries and consumers are always for the production of more efficient, more compact and low cost products. In this light, micro-technologies have gained much interest in the last decades, because of the better performance achieved and the limited space and material required compared to macro-scaled solutions. For this reason, micro-cooling technologies, including micro-finned arrays in forced convection conditions, have been extensively investigated [3–5]. Despite that, only a limited number of researches on naturally convective micro-fins can be found in literature. Kim et al. [6] investigated vertically orientated micro-fins and demonstrated that macro-fin heat transfer correlations could not be used to describe the behavior of micro-scaled systems. Mahmoud et al. [7] experimentally sorted out, for the first time, the correlations between micro-fin geometries and heat transfer coefficients. Even if lower than those of a flat surface, the heat transfer coefficients for horizontal upward facing fins were found to increase when the fin spacing was increased and the fin height was decreased. Recently,

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Micheli et al. [8] reported that the heat transfer coefficient is enhanced by the thickness of the fins. Shokouhmand and Ahmadpour [9] numerically demonstrated the non-negligible contribution of radiation, which accounted for more than 20% of the global micro-fins heat transfer.

Earlier researches mainly focused on the heat transfer coefficients. In real world applications, instead, engineers and system designers look for thermal resistance, compactness, weight and cost of the heat sinks. The present work aims to study, for the first time, the effective thermal enhancement due to the application of micro-fins on a horizontal flat surface by analyzing additional heat sink metrics, such as the individual and overall fin effectiveness and the mass specific heat transfer coefficient. The correlations between geometry and heat sink metrics are explored and commented in the present paper to contribute to optimize the design of micro-fins. The arrays are studied in upward and downward orientations: despite the upward conditions are known to be the best for natural cooling [10], different orientations might be required in some applications [11] and, for this reason, need to be investigated.

2. Heat sink metrics

The previous works [6,7] studied the heat transfer coefficient of micro-fins arrays (h_{fins}), which is described as follows:

$$h_{fins} = \frac{Q_{fins}}{S_{fins} \cdot (T_{fins} - T_a)} \tag{1}$$

where Q_{fins} is the heat dissipated through the fins by convection, S_{fins} and T_{fins} are respectively the surface and the temperature of the finned surface, and T_a is the ambient temperature. In accordance with previous investigations on micro-fins, T_{fins} is considered constant along both the fin height and the length of the array [7,8]. Because of this assumption, no analysis of the fins efficiency has been carried out. Therefore, since no temperature gradient is considered across the finned surface, h_{fins} represents the average of the heat transfer coefficients of the various surfaces of the fins.

The aim of a fin is to increase the heat transfer from a surface to a fluid by increasing the thermal exchanging surface. In practical applications, it is required to understand the effective heat transfer enhancement introduced by the fins if compared to the original flat surface. The heat transfer coefficient measures the thermal property per unit of surface and it is not an indicator of the thermal performance of the heat sink, because it does not take into account the surface extension obtained when the fins are introduced. For this reason, a second parameter, the individual fin effectiveness (ε_f), is generally used [12] to compare the behavior of a single fin and that of a flat surface:

$$\varepsilon_f = \frac{Q_f}{h_{flat} \cdot A_f \cdot (T_{flat} - T_a)} \tag{2}$$

where Q_f is the heat transferred by a single fin, A_f is its cross-sectional area, and h_{flat} and T_{flat} are respectively the heat transfer coefficient and the temperature of the flat plate. Q_f is obtained as:

$$Q_f = h_{fins} \cdot (2 \cdot L \cdot H + 2 \cdot t \cdot H + A_f) \cdot (T_{fins} - T_a) \tag{3}$$

where L is the fin length, H is fin height and t is the fin thickness (Fig. 1). Incropera et al. [13] defines the individual fin effectiveness as the ratio of the fin heat transfer rate to the heat transfer rate that would exist without the fin. ε_f is expected to be as large as possible. A fin array is made of a number of fins: for this reason the overall fin effectiveness (ε_{fins}) has to be considered as well, in order to have a most accurate measure of the performance of the whole fin array [14–16]. The overall fin effectiveness (ε_{fins}) is obtained as the ratio of heat transfer with fins to that without fins over the same area of a flat surface of length L and width W:

$$\varepsilon_{fins} = \frac{Q_{fins}}{Q_{flat}} \tag{4}$$

where Q_{flat} is the heat transferred by the flat plane. The overall fin effectiveness directly compares the heat transferred by the fin array and by the unfinned surface: if $\varepsilon_{fins} > 1$, the fins have enhanced the thermal behavior of the surface.

Micro-fins are usually obtained through material subtractions: along with the effects on the heat transfer, they reduce the mass of the heat sink. This feature becomes particularly important in portable or tracked systems, such as concentrating photovoltaics, where a reduced weight means a reduced load for the tracker [17]. The mass specific heat transfer coefficient measures the effectiveness with which fin material is utilized in the promotion of heat transfer [18] and is expressed as:

$$h_m = \frac{Q_{fins}}{\rho \cdot V_{fins} \cdot (T_{fins} - T_a)} \tag{5}$$

where ρ is the density of the fin material and V_{fins} is the volume of the whole micro-finned heat sink.

3. Experimental investigation

3.1. Micro-fin geometries

A micro-fin is any extended surface with at least one micro-scaled dimension. In the present work, ten plate fin geometries have been considered: the fin dimensions are resumed in Table 1, according to the nomenclature shown in Fig. 1, and numbered from #1 to #10. The fin arrays are diced on 1.4 mm-thick, 50 mm × 50 mm-sized square silicon wafers and their thermal behaviors are compared with that of a flat unfinned silicon wafer.

3.2. Experimental setup

The experimental setup described in Ref. 8 is used, as shown in Fig. 2. The heat is generated by 5 cm × 5 cm-sized electrical heaters (Omega KHLV-202/2.5), regulated using a DC power supply (Weir 413D). The heaters are bonded to the back surface of the silicon wafers through a thin conductive adhesive (3M tape 966, 0.18 W/mK). The power in input (Q_{in}) is calculated by multiplying the input voltage

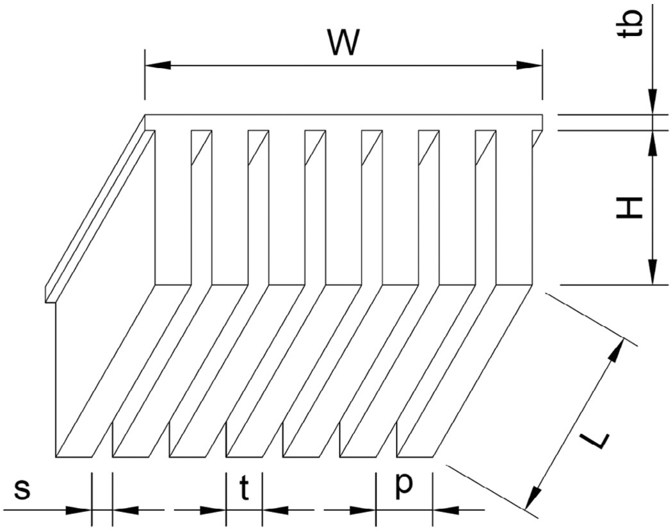

Fig. 1. Horizontal plate micro-fins geometry with typical dimensions.