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Experimental and numerical study on the flow topology of finned heat sinks with tip clearance

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ABSTRACT

An experimental and numerical study is presented that focuses on the flow topology in finned heat sinks with tip clearances. As it is well known, the use of tip clearances has, normally, a global beneficial effect. Typically, heat transfer may degrade (a negative effect) by a somewhat small percentage while pressure drop may decrease (a positive effect) by a substantial amount. In this context, the important question from an R&D standpoint is to understand the flow topology so that the actual design of the tip clearance optimizes the balance between heat transfer and pressure drop. In this study, a 3D numerical method is validated, first, comparing with the Particle Image Velocimetry based experimental results obtained in the actual setup in isothermal conditions. Then, the flow solver thus validated is used in a series of thermal cases in which both the tip clearance height and Reynolds number are varied so as to clarify the flow topology. In particular, it has been found that the behavior of both heat transfer and pressure drop cannot be explained in view, only, of flow development and thermal development aspects. This is so because the Nusselt versus Graetz curves that have been generated do not collapse into a single fit; instead, they collapse into several families that are governed by the tip clearance parameter. Distinct heat transfer rates have been observed for the different fin walls. The transfer rate of the side walls is nearly three times larger than that of the bottom walls, and this suggests the optimum place to locate the heat sources in a practical engineering application.

1. Introduction

A recurrent subject in R&D for thermal engineering application purposes is the potential advantage of implementing tip clearances in heat sink configurations with fins, pin fins, etc, to reduce pressure drop (directly related to pumping power) without imposing a large penalty on heat transfer. This is important in applications in which the pumping power for the cooling fluid cannot be increased at will but, instead, it is prescribed by some global specifications, as it happens, for example, in avionics systems. In these environments, reducing the pressure drop is critical even if a small penalty is to be paid in terms of heat transfer performance. The reason is that the global nature of the system specifications does not account for local hot spots and, thereby, the thermal engineer needs to implement local solutions that allow for an appropriate cooling performance. This happens, also, when addressing the cooling of electronics equipment of computing centers, big data centers, etc.

From an engineering standpoint, this tip clearance approach has the advantage of being passive (no moving parts or external power sources are needed) and robust. The drawback is that a positive outcome, reduced pressure drop, is counterbalanced by a negative one, smaller heat transfer rates. Then, the critical design aspect in actual engineering applications is to find out a reasonable compromise between these two contradicting effects. In this context, reaching a detailed understanding of the flow topology involved may help to approach this goal that is the objective of the present study.

To the knowledge of the authors, the first journal article published in this field was the one of Sparrow et al. [1] back in 1978. They considered a shrouded fin array with and without tip clearance. Later, Sparrow and Kaddle [2] addressed the same geometry from an experimental perspective. Other articles published up to 2010 are those of Wirtz et al. [3], Cretzer and Visser [4], Min et al. [5], Dogruoz et al. [6], Jeng [7], Rozati et al. [8], and Moores et al. [9].

More recently, Reyes et al. [10] carried out an experimental study on the effects of tip clearance on a micro channel based heat sink. The authors considered three different values for the clearance height and compared it to a reference case with no clearance present. The Reynolds number, Re, based on the hydraulic diameter of the flow passages was

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Nomenclature list

Latin symbols

A_w	Wall area [m^2]
C	Configuration
Cp	Specific heat [J/(kg K)]
CS	Cross section [cm^2]
D_H	Hydraulic diameter [cm]
H	Channel height [mm]
h	Heat transfer coefficient [W/(K m^2)]
k	Thermal conductivity [W/(K m)]
L	Channel length [m]
Nc	Number of cells
Nu	Nusselt number
P	Pressure [Pa]
Pr	Prandtl number
Q	Volume flow rate [l/h]
Q_w	Heat transfer rate [W]
Re	Reynolds number
T	Temperature [K]
TC	Tip clearance [mm]
u	Streamwise velocity component [cm/s]
v	Velocity vector [cm/s]
W	Wall
x	Spatial coordinate [m]
y	Spatial coordinate [m]
z	Spatial coordinate [m]

Greek symbols

ε	Deviation
ρ	Flow density [kg/m^3]
μ	Flow viscosity [kg/(m s)]

Subscripts

∞	Conditions at the inlet section

varied between 400 and 2600. The working fluid was water and the heat sink wall temperature was kept constant and equal to 70 °C. At the lowest Re, the authors found that pressure drop and heat transfer were very sensitive to the tip clearance. The optimum configuration was the one in which the tip clearance (500 μm) was equal to the fin height. In this case, the ensuing Nusselt number, Nu, was 0.83 times the reference Nu, while the pressure drop, ΔP, was 0.20 times the reference ΔP. However, for the highest Re, it was observed that both heat transfer and pressure drop showed a weak dependence on the tip clearance. Specifically, heat transfer degradation and pressure drop improvement rates at the higher Re were similar regardless of the tip clearance height.

Tullius et al. [11] addressed the problem of optimization of micro pin fins in minichannels. Their study was of a numerical nature and several clearance ratios were considered. They reported the contradicting effect of pressure losses versus heat transfer mentioned earlier. In particular, they showed that pressure drop had a greater sensitivity with regard to the problem governing parameters than heat transfer. Interestingly enough, they were able to generate a correlation for Nu that accounted for the tip clearance height as well. An experimental study on the influence of the tip clearance in a group of micro-cylinders placed on a heat sink has been described by Liu et al. [12]. The authors concentrated on the low Re regime and for Re 400 and the optimum clearance they reported a 15% deterioration of heat transfer and a 50% reduction of pressure losses as compared to their reference case. Liang et al. [13] have extended these studies to the case in which the working fluid is non-Newtonian (power-law polymeric in their case) and found similar qualitative trends. Mei et al. [14] studied the effect of tip clearance in micro-pin type geometries and reported heat transfer degradation rates of the order of 50% with reduction of pressure losses by a factor of about 4.

The effect of tip and lateral clearance on a new heat sink concept has been addressed by Ho et al. [15]. In this article, besides an experimental study, the authors proposed a semi-analytical model that could be used for designing purposes. An experimental study that accounts for, among other aspects, the influence that tip clearances have on the thermal performance of pin-fin arrays has been published by Li [16]. In this study, the authors were able to find linear correlations between thermal performance, Re and tip to outer surface distance. Jadhav and Balaji [17] have presented yet another experimental study and it is worth to note that they report in their conclusions that the effect of tip clearance on thermal performance is more pronounced at lower flow velocities. Finally, it is worth mentioning the computational study of Giri and Das [18]. These authors considered a shrouded rectangular fin array and they varied clearance spacing, fin spacing and Re. In their conclusions they suggested the presence of potentially optimum values for the clearance.

Summarizing, there is a common qualitative tendency in all the above mentioned references regardless of the type of geometry under consideration (square section pin fin, circular section pin fin, conventional straight fin, etc.). Namely: the main effect of tip clearance is to degrade heat transfer somewhat while alleviating pressure losses significantly. However, actual quantification of these effects appears to be very much problem dependent. So, in this context, the objective of the present study is to focus on a single, and very general, geometry, heat sink with straight fins and tip clearance, and clarify its actual flow topology. To do it, the study being presented is of a dual nature: experimental and numerical. Obviously, it would have been much better to perform a fully experimental work. However, the geometry being considered was three dimensional and complex, and the most reliable information provided by the Particle Image Velocimetry technique, PIV, was limited to some specific planes that were not fully representative of the actual 3D topology. Then, the strategy was to perform a series of isothermal experiments on the test model and use the results to validate the 3D flow solver via comparison with local PIV data. Then, thus validated, the flow solver was applied to the thermal cases. Regarding organization of the article: section 2 describes the experimental setup, section 3 presents the flow solver, isothermal experimental results and comparison with their numerical counterparts are given in section 4, computational thermal cases are presented and discussed in section 5, and, finally, conclusions are stated in section 6.

2. Description of the experimental setup

The experimental model was manufactured out of methacrylate. It basically consisted of four square section channels connecting two stagnation chambers. The cross section dimensions of the channels were 10 mm × 10 mm and their length was 250 mm. The upstream stagnation chamber had the following dimensions: length 200 mm, span 90 mm and depth 20 mm. The dimensions of the downstream stagnation chamber were: length 50 mm, span 90 mm and depth 20 mm. It could be observed that the depth of the stagnation chambers (20 mm) was twice the channel cross section height (10 mm). This means that the flow had to go through a forward step like structure before entering the channels. A sketch of the basic platform is shown in Fig. 1.

Three different models were manufactured: the so-called configurations C0, C1 and C2. Configuration C0 was the reference configuration because the top cover was pressed directly over the fins (no tip clearance present). In configurations C1 and C2 the covers were