Assessment of Periodic Flow Assumption for Unsteady Heat Transfer in Grooved Channels

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Numerical studies of unsteady heat transfer in grooved channel flows are made. The flows are of special relevance to electronic systems. Predictions suggest a commonly used periodic flow assumption (for modeling rows of similar electronic components) may not be valid over a significant system extent. It is found that the downstream flow development is strongly dependent on geometry.

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1 Introduction

With increasing power densities, the reliable computation of heat transfer in electronic systems is becoming even more important [1–3]. The grooved channel flow (see Fig. 1), which simulates rows of integrated circuits (ICs) on a circuit board, is especially relevant to electronics cooling. At Reynolds numbers relevant to electronics, grooved channel flows can become unsteady. This can strongly affect heat transfer [1,2,4]. Here, the Reynolds number is defined as Re=Uc/hv where Uc is the centerline velocity and h the channel half height.

Ghaddar et al. [5] studied idealized two dimensional (2D) isothermal cyclic flow in channels with IC-like protrusions. For Reynolds numbers larger than a critical value (Re0), cyclic flow oscillations which increase fluid transport are observed. Ghaddar et al. [6] use two dimensional nonisothermal predictions to illustrate the potential for naturally enhancing heat transfer using the unsteadiness observed by Ghaddar et al. [5]. Amon and Mikic [7], Amon [8], and Nigen and Amon [9–11] extend the above work, comparing heat transfer enhancement for flows where oscillations are induced passively and naturally when Re>Re0. Wang and Vanka [12], Greiner et al. [13], and Nishimura and Kawamura [14] studied oscillatory flow in wavy-walled channels. They observed similar heat transfer enhancement.

Importantly, due to computational resource constraints, all of the above work assumes periodic flow. The question remains unanswered as to how realistic this assumption is in a practical electronics design context (i.e., over what percentage of a circuit board is the periodic flow assumption valid). Exploring this is the objective of the present work.

2 Governing Equations and Numerical Method

The unsteady Navier–Stokes and continuity equations can be written in the following nondimensional incompressible flow form:

\[ \frac{\partial u_i}{\partial x_i} = 0, \]  
\[ \frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\nu}{\partial x_j^2}, \]  
\[ \frac{\partial T}{\partial t} + \frac{\partial T u_i}{\partial x_i} = -\frac{k}{\rho C_p} \frac{\partial^2 T}{\partial x_i^2}. \]

In the above, \(u_i\) is the instantaneous velocity in the \(x_i\) direction, \(t\) is time, \(p\) is the pressure, and \(T\) temperature. Here \(\rho\) is the fluid density, \(k\) thermal conductivity, and \(C_p\) the specific heat capacity.

2.1 Boundary Conditions. Parabolic inlet velocity profiles are used. At outflow boundaries, to suppress wave reflections, a convective boundary condition [15,16] is applied. At solid walls, the no-slip and impermeability conditions are used. The temperature of the incoming flow is constant at \(T_i\). For relevance to heat transfer from ICs, the temperature of the block is \(T_b>T_i\). The temperature of the other walls is constant at \(T_i\).

2.2 Numerical Scheme. The governing equations are solved using a standard well-verified finite volume method (see Refs. [3,17]). Time integrations use a second-order Crank–Nicolson scheme for both the convective and viscous terms. For the spatial discretization, second-order central differences are used.

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used. Temporal resolution effects are investigated by successively halving time steps until no substantial differences are observed. To resolve high shear, a hyperbolic tangent grid stretching is used. Most simulations are run on a 1430×65 nonuniform grid. A grid independence study is made using a 2070×65 grid. Time steps of $\Delta t = 0.02$ are used. Typically, simulations contain 10 blocks. A comparison has been made with the experimental data of Tropea and Gackstatter [18] for flow in a single groove channel. The present results are in good agreement with these measurements.

3 Results and Discussion

The block height is $a/h = 1$ and the spacing between neighboring blocks $(b + g)/h = 10$, where $b$ is the block width and $g$ the groove width. The first block is located at $x = 10h$ (i.e., the upstream side of the block is located at $x = 10h$ and the downstream at $x = 10h + h$).

Preliminary simulations are used to determine $Re_c$. For this test, just $b/h = 2$ and $g/h = 8$ are considered, giving $Re_c > 155$. Therefore, to ensure unsteady flow for all geometries ($b/h = 2$, 4 and 6), $Re = 500$ is used.

3.1 Mean Flow Distributions. For $b/h = 2$, the recirculating flow region downstream the block is small compared to $g$. For $b/h = 6$, $g$ is too short for the recirculating flow to reattach on the lower channel surface between the blocks. For $b/h = 4$, the recirculating region size is comparable to $g$. Time-mean streamline and temperature contours are shown in Figs. 2 and 3, respectively, for the three $b/h$ values. As can be seen from Figs. 2 and 3, with increasing $x$ the flow tends to a "periodic state." In this region, a single block could be considered with periodic streamwise boundaries.

For $b/h = 2$ (see Figs. 2(a) and 3(a)), the flow development along the groove surface after the reattachment is quite independent of the recirculating flow upstream and the flow reaches a "periodic state" relatively quickly. After the first block, the flows become unsteady. This increases with $x$ and eventually, the unsteady fluctuations become the same order of magnitude as $U_m$.

3.2 $C_f$ and Nu Distributions. Figures 4 and 5 show the downstream development of $C_f$ and Nu over block surfaces for $b/h = 2$, 4, and 6. The definitions of $C_f$ and Nu are:

$$C_f = \frac{dU}{dy} Re,$$

$$Nu = \frac{h}{\Delta T} \frac{dT}{dy}.$$

where $\Delta T$ is the temperature difference, $T_b - T_i$. A new coordinate $s$ is introduced such that $s = 0$ indicates the upstream corner of each block. Note, for a fully developed plane channel flow $C_f = 2$. The strong $C_f$ singularities at $s = 0$ are caused by the sharp groove edges. For all $b/h$ values the $C_f$ profiles change substantially with $x$ for $x < 30$ (the third block). The negative $C_f$ peak has a fully developed value around the fifth groove. Fluctuating kinetic energy ($k$) against $x$ is also examined (not shown here). The
measuring points are $3h$ downstream of each block and at $y/h = 1$. Consistent with the negative peak $C_f$ evidence, after the fifth block, $k$ reaches a quasifully developed value. After this, the region, flow periodicity could be assumed. Figure 5 shows that the heat transfer is much lower for the first few blocks, prior to reaching "quasiperiodicity."

Figure 6 shows the interblock $C_f$ and Nu distributions for $b/h \sim 6$. For this $b/h$, the recirculating flow impinges on the vertical upstream surfaces of the blocks ($C_f_U$). The flow development toward the "quasiperiodic" state is much slower between the block compared with over the block surface (shown in Figs. 4 and 5). A comparison of $C_f$ and Nu suggests that the thermal boundary layer development is much slower than that of the flow field. The cases with $b/h = 2$ and 4 show similar trends although the approach to the "quasiperiodic" state is slightly faster.

Figure 7 highlights the downstream development of the flow using averaged surface properties. The average $C_f$ and Nu over block surfaces and between them is given. The subscript $U$ represents upstream block face values, $A$ a block surface average and $I$ interblock values. Studying $C_f_U$ shows that as $b$ increases, the flow takes longer to develop. For $b/h = 2$, $C_f$ does not change much along the downstream direction while $b/h = 4$ and 6 accompany significant changes. For example, for $b/h = 6$, $C_f_U$ attains a "periodic value" after block four. For $b/h = 4$, the recirculating flow region downstream of the first block is as large as $g$, resulting in negative shear (see also Figs. 2(b) and 4(b)). Importantly, it takes longer distance for the actual velocity fluctuations to become periodic. Figures 7(b) and 7(c) indirectly give thermal field data. It is clear (cf. Figs. 7(a)–7(c)) that the periodic flow assumption can be more problematic for the thermal field. Figures 7(b) and 7(c) show that the thermal field develops more slowly with increasing $b/h$. For example, with $b/h = 6$, Nu $A$ changes even after the sixth block.

4 Concluding Remarks

Numerical studies of unsteady laminar flow heat transfer in grooved channel flows of especial relevance to electronic systems are made. The validity of a commonly used periodic flow assumption is explored. Predictions for Re = 500 show the flow typically can become periodic by around the fifth groove. Hence, when modeling IC rows on circuit boards the periodic flow assumption might not be valid for a significant area.
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References


Fig. 7 Average $C_f$ and Nu around the block: (a) $C_f$, (b) Nu, and (c) Nu.