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Experimental and numerical investigation of natural convection in a discretely heated vertical channel: Effect of the blockage ratio of the heat sources

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A B S T R A C T

This study deals with the buoyancy induced flow and heat transfer in a parallel plate channel with a heat source array, which simulates an electronic package. The heat source array consists of four discrete protruding heat sources made of copper. The focus of this study is concentrated on the effect of heat source blockage ratio (b_r) on recirculating flow and cooling performance of the system. Studies are conducted both for flush mounted or protruding heat source cases. Four different values of the blockage ratio of the protruding heat sources (b_r = 0.125, 0.25, 0.375 and 0.5) are considered. The range of the modified Grashof number covers the values between 9.6×10^5 and 1.53×10^7. In the experiments, flow visualization and temperature measurements are conducted. Numerical studies are performed via ANSYS Fluent software. From the experimental results and numerical studies, it is found that buoyancy induced flow and cooling performance is significantly affected by the blockage ratio of the heat source array.

1. Introduction

As dimensions of electronic devices downscale day by day, heat generated by a circuit component increases due to the increased processing capacity. In cooling of electronic packages, it is quite important to remove excessive heat from the system and to ensure uniform temperature distribution within the package. The thermo-mechanical stresses that result from excessive temperature rise causes catastrophic failures such as breaking the solder joints, melting or burning of the low-temperature materials. In addition, functional irregularities of the components can be caused as a result of overheating [1]. For these reasons, effective cooling and thermal management is very important in terms of ensuring continuous and reliable operation.

Electronic packages consist of flush mounted or protruding heat generating components with different shapes and sizes. These components cause vortex formation in the flow field, and the amounts of heat transfer by convection and radiation vary depending on the changing heat transfer surface area. For this reason, relevant flow and heat transfer mechanisms must be analyzed for an effective cooling, and design of the electronic package must be made accordingly. There are a vast number of studies on the cooling of electronic packages with different geometries and flow regimes. Here, studies on the convective heat transfer in parallel plate channels with protruding heat sources will be considered only because of the content of the study. The majority of these studies have addressed the effects of Reynolds number, Grashof number, channel parameters, wall-to-fluid thermal conductivity ratios, radiation heat transfer between surfaces, channel inclination, distribution of the applied power between the heat sources and heat source(s) size(s) as well as heat source(s) spacing(s) on convective heat transfer and fluid flow.

Natural convection inside a parallel plate channel with protruding heat sources were investigated in Refs. [2–8]. Fujii et al. [2] conducted an experimental study on natural convection in a stack of parallel plates with protruding heat sources. For Grashof numbers between 2.3×10^3 and 8.8×10^5, they examined the effect of the aspect ratio of the plates on fluid flow and heat transfer. Bessaih and Kadja [3] studied conjugate, turbulent natural convection in a vertical adiabatic channel with three discrete ceramic heat sources, focusing on the effects of unheated heat source on cooling of the heat generating components. They claimed that the surface temperatures of the heat sources were uniform, an increase in the distance between the sources allowed for better cooling, and more efficient cooling was realized when the unheated component was placed between the other two components. Desrayaud and Fichera

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Nomenclature

A_s	surface area [m^2]
b	heat source width
b_r	blockage ratio, $b_r = b/W$
D	channel depth [m]
D_h	hydraulic diameter [m]
F	view factor
g	gravitational acceleration [m/s^2]
Gr^*_{Dh}	modified Grashof number, $Gr^*_{Dh} = g\beta\dot{q}D_h^4 t_h/k\upsilon^2$
h	convective heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/mK], turbulent kinetic energy [m^2/s^2]
L	length [m]
Nu	local Nusselt number, $Nu = hD_h/k$
Nu_{ave}	average Nusselt number, $Nu_{ave} = h_{ave}D_h/k$
p	pressure [Pa]
q	heat flux [W/m^2]
Q	power [W]
s	clearance between the heat sources [m]
t	thickness [m]
u_i	velocity component [m/s]
T	temperature [°C]
W	channel width [m]
x_i	coordinate direction

Greek letters

β	thermal expansion coefficient of the fluid [1/K]
ε	surface emissivity
ϵ	turbulent dissipation rate
μ, μ_t	laminar and turbulent viscosities
ρ	density [kg/m^3]
δ_{ij}	Kronecker delta

Subscripts

$'$	fluctuation
ave	average
cond	conductive
conv	convective
cu	copper
f	fluid
in	inlet
ins	insulator
j,k	surfaces
out	outlet
p	polycarbonate
rad	radiative
s	solid
tot	total
0	reference value

[4] investigated two dimensional natural convection in a vertical channel with a protruding heat flux module numerically. They developed a correlation for the heat source temperature for various lengths and heights of the protruding heat source. Avelar and Ganzarolli [5] performed an experimental and numerical study on an array of vertical parallel plates with heat generating protruding components to investigate uniform and non-uniform heating conditions. In the non-uniform heating condition, one of the heat sources had a different heat production than others. The effect of the source location with different heat production on temperature distribution was studied. They reported that periodically-fully developed flow occurred between the second and fifth heat sources in the position of the plates closest to each other. In the case of non-uniform heating, they determined that the most heated component had a limited effect on temperature distribution but it increased the temperatures of the components behind it. Icoz and Jaluria [6] numerically investigated the onset of instability in natural convection in a rectangular channel heated by identical discrete heat sources from its bottom surface. Parameters such as surface temperatures, channel dimensions, openings, boundary conditions, and positions of the heat sources were investigated in this study. They determined that the channel dimensions and presence of openings had significant effects on the flow. However, their effects on heat transfer were limited. An increase in channel height increased instability and caused a decrease in critical Grashof number. Desrayaud et al. [7] investigated steady, two dimensional natural convection in a stack of parallel vertical channels with a single protruding heat source module to investigate heat transfer and flow characteristics. They performed a parametric study by varying thermal conductivity and thickness of the substrate and width of the module. They reported that axial conduction through the substrate was important for cooling mechanism and must be accounted for. Durgam et al [8] investigated natural and forced convection cooling of a heat source array mounted on a vertical and horizontal board numerically and experimentally to find optimum heat source position in different convection regimes. They stated that the highest heat generating components should be positioned close to the bottom corners of the board, and the effect of the thermal conductivity of the board on the maximum excess temperature was significant.

Some of the regarding studies on mixed convection are Refs. [9–14]. Du et al. [9] numerically analyzed mixed convection in a vertical channel with discrete protruding heat sources mounted on a surface. The inlet and outlet lengths of the channel and positions of the heat sources were discussed, and increasing values of the Reynolds number and decreasing values of the Rayleigh number were found to increase convective heat transfer to the unheated wall. Particularly at the lower values of the Reynolds number, temperatures of the heat sources decreased with an increase in Reynolds and Rayleigh numbers, and the effect of the Rayleigh number was limited at the higher values of the Reynolds number. Premachandran and Balaji [10–12] examined conjugate mixed convection from horizontal and vertical channels in which protruding heat sources mounted on one of the walls with or without surface radiation for different working fluids. Reynolds number, modified Grashof number, Prandtl number, thermal conductivities of the heat sources and substrate, and surface emissivities of the heat sources varied while the geometric parameters related to the channel and protruding heat sources were constant in these studies. They reported that radiation heat transfer was considerable at lower Reynolds number values, maximum temperature decreased with increasing values of the Reynolds number, modified Grashof number, and thermal conductivities of the heat sources and substrate. Hamouche and Bessaih [13] and Boutina and Bessaih [14] investigated laminar mixed convection numerically in horizontal and inclined channels with two identical protruding heat sources, respectively. They focused on the effects of inclination of the channel, Reynolds number, dimensions of the heat sources and clearance between the heat sources on flow and heat transfer.

Similarly, Refs. [15–29] are some examples for regarding studies for forced convection. Davalath and Bayazitoglu [15] studied two dimensional conjugate forced convection across rectangular heat sources in a parallel plate channel numerically. They focused