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1. Statement of Problem Studied

1.1 Introduction

The primary goal in semiconductor heat sink design is simple. It is to increase the heat transfer while decreasing the momentum resistance as for regular closed type heat exchangers is the goal. Nevertheless, as soon as everyone agrees that the best way to achieve the maximum heat transfer rate within a particular volume of heat sink is through the introduction of additional heat exchanging elements (ribs or pins of different shape) the problem becomes a two scale heterogeneous volumetric heat exchanger design problem. The processes on the lower scale heat transport -- in and around a single transfer element (rib, fin) no longer describe the heat transfer rate of the whole sink. At the same time, the formulation of the problem of a heat sink for a one-temperature, or even a two-temperature homogeneous medium does not involve or connect the local (lower scale) transport characteristics determined by the morphology of the surface elements, directly to the performance of heat sink nor does it give guidance on how to improve the performance characteristics.

The two morphologies we were dealt with in this study of heat sink design were researched numerous times based on conventional one scale heat transfer-fluid mechanics descriptions see, for example, among others the works by Bejan and Sciubba (1992), Bejan and Morega (1993), Bejan (1995, 1999), Kim and Kim (1999), You and Chang (1997). The major problem with these approaches is that their formulations (and consecutive experimental or theoretical studies) are done on the lower scale (homogeneous) of description -- but the answers have been sought for the upper scale -- general scale of the heat transfer device. As we mentioned, this gives the gap between the formulations and the goals. Thus, Bejan and Morega (1993) while comparing the pin fins and plate fins morphologies of heat exchanger in laminar regime could not come to a conclusion -- which of the structures is the best and why? Their answers are given in terms of local descriptive characteristics as optimal pin fin diameter and local thermal conductance. Meanwhile, in the work published by Bejan (1999) recently, the approach named by author as ``constructal theory" appeared to be the one which started the hierarchical scaling VAT many years ago (more then 30 actually) - ``The optimization proceeds in a series of volume subsystems of increasing sizes (elemental volume, first construct, second construct. The shape of the volume and the relative thickness' of the fins are optimized at each level of assembly."

The work by Kim and Kim (1999) was based on the Vafai and Tien's model for porous medium laminar flow regime equation. The nondimensional set of convective heat transfer equations does not have the correspondence to morphological parameters of the problem so, the authors studied the influence of channel's aspect ratio ($H/w_s=a_s$, w_s is the channel width), and the ratio of effective conductivities set up in the problem on the profiles of velocity and temperature.

We are mostly interested, as in earlier studies, in question of how the device behaves in experiments and in the corresponding mathematical simulation as a whole unit. At the same time we are not engaged into the balance studies conventional in the heat exchangers technology.

1.2 Objective and Studied Problems

1) Develop method for optimized design of semiconductor heat sink (SHS) for removal of a heat flux resulted from a heat spreader, based on the heterogeneous scaled VAT approach. Provide recommendations for optimized design of confined Air-Cooled SHS.

2) Develop mathematical models, procedures and codes for simulation of heterogeneous scaled SHS VAT governing equations.

3) Design an experimental method, models for it and data reduction algorithms for SHS experiment to verify and support the VAT design method.

4) Develop initial sufficient basics for new class of Heterogeneous Medium Distributed Parameters partial differential governing equations Optimization Problem (HMDPOP) solution which models the SHS performance.

5) Provide the DOE optimization search and the first approximation SHS design based on the regular medium VAT heterogeneous model and code.

6) Develop methods, models and codes for embedded scaling simulation of VAT design using the CFD solver.

2. Summary of the Most Important Results

2.1 Ideology Behind the Two-Scale Approach in Modeling and Simulation of the Complex Heat Transfer Devices

Development of a heterogeneous two-scale VAT mathematical basis and models for optimization of a heterogeneous, hierarchical scaled media began with work by Travkin, Gratton and Catton (1994) and is followed by a series of papers Travkin and Catton (1996-1999) documenting the development of a method that is applicable to a wide variety of transport phenomena ranging from fluid mechanics to crystal photonic band-gap problems, clearly demonstrating the interdisciplinary nature the multi-scale VAT description of transport phenomena. The theoretical development of transport phenomena in heterogeneous media with multiple scales has now been brought to the level where a specific application can be chosen for demonstration. The application chosen is enhancement of heat transfer dissipation from a heterogeneous media while minimizing the frictional resistance (a problem of importance to all designers of heat exchangers). This problem has been under investigation for more than 3 decades and in spite of its longevity and importance as a problem, it has not been satisfactorily treated.

A majority of past investigations focused on solutions to a specific optimization task with a very limited number of spatial parameters to be varied, usually a fixed geometric configuration, that they tuned in their search for a maximum level of heat exchange (see, for example, Bejan and co-authors (1992,1993,1995,1999,etc.) and references therein). This approach is a "single-scale" approach yielding an optimum for certain morphology and flow intensity without giving an explanation for why it was achieved. Without an explanation, there is no guidance on how to change the design to improve its performance. Approaching the experiment for each new morphology, whether real or numerical, needs to be performed again. In the heat exchanger industry there are countless research studies devoted to this problem.

In current study outlined how earlier results by Travkin and Catton (1994,1998, 2001a), Catton and Travkin (1997), and Gratton et al., (1996) were applied to a practical application as design of SHS. The present treatment of the heat exchange optimization process can be applied to any specific hierarchical heterostructure with the aim to optimize its performance.

Contrary to the homogeneous medium transport mathematical formulations - the scaled heterogeneous medium mathematical models and governing equations composed in such a way that they contain the additional terms reflecting physical phenomena which are important in heterogeneous medium transport and can not be seen or included in the traditional homogenous formulations.

That means, that these additional effects should find their ways to the description or models which reflect the characteristics of performance of the complicated heterogeneous device.

2.2 Lower (First) Scale Laminar and Turbulent Conjugate Heat Transfer Problem Statements in the SHS's

In this study we used both the laminar and the turbulent flow regimes applied for problem analysis. The problem's mathematical statement for the lower scale homogeneous formulation when the momentum flow is low in volume is the laminar problem formulated as the 3D one-temperature model $\overline{\mathbf{V}}\nabla\overline{\mathbf{V}} = -\nabla\overline{p} + \frac{1}{Re_d}\nabla^2\overline{\mathbf{V}}$, $\overline{\mathbf{V}}\nabla\overline{T} = \frac{1}{Pe_d}\nabla^2\overline{T}$, then, it would be much more advantages if the mathematical model accounts also for the solid phase temperature distribution as, for example, applying the equation for the second temperature (solid phase) $\nabla^2\overline{T}_s = 0.$ Meanwhile, for the great number of situations the flow regime in the heat sink is turbulent. Bounded by this restriction the model for the heat transfer inside and around of the SHS should be constructed as for the turbulent heat transport in the fluid (air) and with the strict compliance to the conjugate boundary conditions within (inside) the volume of the SHS. The full set of turbulent governing equations were used for the lower scale exact simulation of the SHS - Travkin et al. (2001c).

2.3 Upper (Higher or Device) Scale VAT Laminar and Turbulent Heat Transfer Statements in SHS

The upper scale VAT governing equations have usually many more governing terms in their formulations. Many of these terms are medium sponsored – reflecting the features of the heterogeneous medium morphology and the physical phenomena, which are not included in the one scale physics of the problem. As, for example, the full scale turbulent momentum equation on the upper (second) scale of the two scale device as SHS used in our studies is

$$\frac{\partial}{\partial x_j}\left(\langle m\rangle \widetilde{\widetilde{U}}_j \widetilde{\widetilde{U}}_i\right) = -\frac{1}{\varrho_f}\frac{\partial}{\partial x_i}\left(\langle m\rangle \widetilde{\widetilde{\overline{p}}}\right) + \frac{\partial}{\partial x_j}\left\langle -\overline{u_j' u_i'}\right\rangle_f + \frac{\partial}{\partial x_j}\left\langle -\widehat{\overline{u}}_j \widehat{\overline{u}}_i\right\rangle_f -$$

$$-\frac{1}{\varrho_f \Delta\Omega}\int\limits_{\partial S_w} \overline{p}\cdot \vec{ds} - \frac{1}{\Delta\Omega}\int\limits_{\partial S_w} \overline{U}_j \overline{U}_i \cdot \vec{ds} - \frac{1}{\Delta\Omega}\int\limits_{\partial S_w} -\overline{u_j' u_i'}\cdot \vec{ds} + \langle m\rangle \widetilde{S}_{U_i},\ i,j = 1-3,$$

where there are the four additional terms in comparison with the lower homogeneous scale turbulent governing equation. To be able to perform much greater volume of work for the two-scale mathematics, in this study were used along with the full two scale statements, also the simplified VAT (SVAT) heat sink governing equations. The six nondimensional parameters for the laminar regime were used in the simplified VAT (SVAT) heat sink governing equations mathematical statement for the upper scale SHS optimization analysis. Among these parameters are specifics for the flow resistance, heat transfer in both phases, and interface and boundary conditions criteria

Name	variable	minimum	maximum	No.
L_{3N}	$= Re_{mf} c_d$	10^{-5}	5×10^7	1
L_{M4N}	$= Re_{mf}(1/m_0)$	10^{-3}	10^5	2
L_{P5}	$= \frac{1}{Pe_m}$	2.1	2×10^7	3
L_{P6}	$= \alpha_L^* = \frac{\alpha_L(z)}{\alpha_{Lm}}$	1.0	10^8	4
L_{P7N}	$= \frac{Pe_m}{A_k(L_{M4}-1)}\alpha_L^*$	0	10^{20}	5
L_{B8}	$= \frac{A_k}{Pe_m} = A_k L_{p5}$	10^{-3}	10^{12}	6

The turbulent regime SVAT governing equations appeared having the eight nondimensional parameters for the constant morphology features.

variable	definition	minimum	maximum	No.
L_{P2}	$= K_w = \frac{\nu}{z_m u_m} = \frac{1}{Re_{mf}}$	10^{-3}	10^3	1
L_3	$= c_d \cong f_f$	10^{-2}	5×10^6	2
L_{M4}	$= A_4 = 1/m_0$	1.0	10^3	3
L_{P6}	$= \alpha_T^* = \alpha_T^*(u^*, m^*, S_w^*) = \frac{\alpha_T}{u_m c_{pf}\rho_f}$	1.0	10^8	4
$L_{P7N}(z)$	$= \frac{Pe_m}{A_k(L_{M4}-1)}\alpha_T^* = const$	0	10^{20}	5
L_{P8}	$= \sigma_b = \frac{\widetilde{K}_m}{K_b}$	0.1	10	6
L_{B8}	$= \frac{A_k a_f}{z_m u_m} = \frac{A_k}{Pe_m} = A_k L_{p5} = const$	10^{-3}	10^{12}	7
L_{B9}	$= \frac{1}{Pe_{TB}} = K_{TB}^* = \frac{a_{TB}}{z_m u_m}$	?	?	8

2.4 Heterogeneous Upper Scale Heat Exchange Control Parameters Used

The analysis of the variables, which are the most looked after in this problem, starts with their definitions. One can observe that most of variables which usually modeled or measured in the SHS technology are non-local. Below are given few of the most pertinent variables and their actuall meanings. Thus, the main variables in the problem like temperatures and velocity are not point variable taken into any formula or analysis equation, they are averaged or through the cross-section, or through the more or less substantial portion of the heat sink volume - as, for example, the simple and powerful morphology of longitudinal fins HS, Fig. 1. So, one can write down meanings of these fields as

$$T_s \equiv \{T_s\}_s, \; \overline{T}_f \equiv \{\overline{T}_f\}_f, \; \overline{\mathbf{V}} \equiv \{\overline{\mathbf{V}}\}_f.$$

because usually the values of these fields being taken as somehow averaged (mean, bulk) variables, that means that experiment should be matching to not just a local (point, dot assigned) physical variables. This fact mostly just ignored in the data reduction and analysis theories and procedures. The bottom surface heat fluxes into fluid and solid sub-volumes of the heat sink are averaged through the respected sub-volumes

$$\mathbf{q}_{wf} \equiv \{\mathbf{q}_w\}_f, \; \mathbf{q}_{ws} \equiv \{\mathbf{q}_w\}_s,$$

and in any way the general estimation of these variables is valid and at the same time interesting data when they are assessed as averaged through the surface or volume local measurements. The very important issue of pressure drop might has a tremendous impact if found or chosen improperly. This is one of the topics where the only lower scale Detailed Micro-Modeling - Direct Numerical Modeling (DMM-DNM) does not hold an answer.

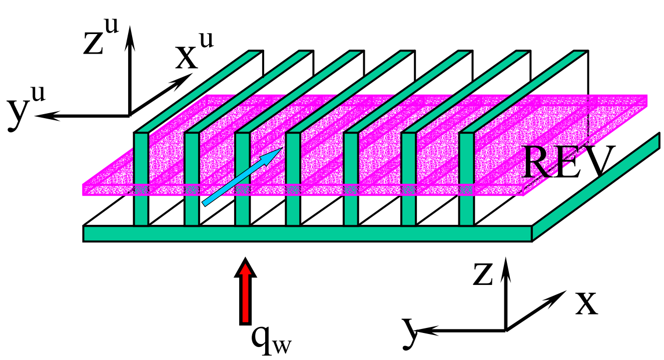

Figure 1 Longitudinal fins heat sink – relation between lower and upper scale representations, unit vectors are the same but scales are different. This REV is moving along of 0-z^u axis during the averaging and closure calculations.

Our DMM-DNM simulation shown (Figure 2) that pressure field is changed in a very strong fashion at the entrance and exit of the heat exchange. Of coarse, it is known fact, but the question with regard of this fact is - At which location, and at what point to take or measure the pressure field to be used consecutively in the VAT procedures, even if it is taken as the local value? If one takes pressure measurements at points outside the volume of heat sink - that means the substantial uncertainty in measured values must be accepted, because the pressure changes highly nonlinear at these regions - at the entrance and exit of the heat sink. To take pressure drop at two points inside of homogeneous morphology heat sink is the way to avoid complicated problems of pressure change at entrance and exit. Also, in this situation the pressure is practically a linear function inside of the HS and the pressure gradient is the same almost at every point inside of the heat sink.

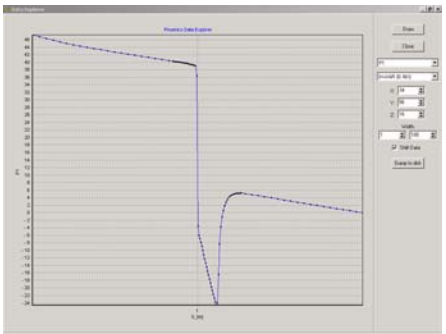

Figure 2 Pressure change along the experimental channel with the heat sink

The following VAT upper scale performance parameters were obtained using the VAT averaging of interface fluxes. The heat transfer rate in the whole device including the bottom heat exchange

$$\vec{\tilde{H}}_{rs} = \frac{S_{ws}\left\{\vec{\mathbf{q}}_w\right\}_s}{\Omega(T_{wmax}-T_{in})} =$$

$$= \frac{S_{ws}}{\Omega(T_{wmax}-T_{in})}\left(-k_s\nabla\tilde{T}_s - \frac{k_s}{\Delta\Omega_{sb}}\int_{\partial S_{ws}}\hat{T}_s\, d\vec{s}_1\right),$$

$$\vec{\tilde{H}}_{rbf} = \frac{S_{wb}\left\{\vec{\mathbf{q}}_w\right\}_f}{\Omega(T_{wmax}-T_{in})} = \frac{S_{wb}}{\Omega(T_{wmax}-T_{in})} \times$$

$$\times\left(-\tilde{K}_T\nabla\tilde{\tilde{T}}_f - \left\{\hat{K}_T\nabla\hat{\tilde{T}}_f\right\}_{fwb} - \frac{\tilde{K}_T}{\Delta\Omega_{fb}}\int_{\partial S_{wb}}\hat{\tilde{T}}_f\, d\vec{s}\right),$$

from here one can estimate the heterogeneous effectiveness's at the SHS heat entrance boundary $\vec{\tilde{E}}_{effs} = \frac{\vec{\tilde{H}}_{rs}}{P_p}$, $\vec{\tilde{E}}_{eff,bf} = \frac{\vec{\tilde{H}}_{rbf}}{P_p}$, $\left[\frac{1}{K}\right]$. As it is appeared we have the vector effectiveness's, which, from now on give the possibility to know in which direction the heat is utmost intends to flow. This, in turn gives the schematic of the "reason – consequence" performance as the one that is more exact and valuable as we observed in the course of this study.