2.10 "Inside the Class" Optimization of the Pin Fin SHS Using the Combined \ Upper Scale Heterogeneous Model and the DOE Simulation Method

By application of SVAT closure models to some general morphology models (as rough and porous layers and channels, capillary and globular morphologies), it was demonstrated earlier that the both transport models on upper scale and the closure schemes can be exact. At the same time, studying the limiting cases of porosity in the channel highlighted mistakes in other studies. The numerical results demonstrate how the simplest morphological properties of a porous layer such as porosity function and specific surface along with closure models naturally affects the transport features and and that it can be helpful in the development of optimized morphologies.

When the optimization criterion (objective function) is chosen, in our situation these are the heat transfer rates, minimum of temperature difference, and an effectiveness, the variables are systematically defined, see the table of parameters developed above. Next, the numerical experiment design type is selected, e.g. as a classical two level, mixed level, or nested level. The design type used in this work is the classical two level design. The classical two level designs are based on standard orthogonal arrays that contain two levels for each experimental variable. It enables estimation of the effects of some or all terms in a second order model of the general form

$$E_{ff} = a_0 + a_1X_1 + a_2X_2 + \ldots + a_nX_n + a_{11}X_1^2 + a_{12}X_1X_2 + \ldots + a_{n,n-1}X_nX_{n-1} + a_{nn}X_n^2$$¶

The independent variables $X_{1,}X_{2,}\ldots X_n$¶ are the design variables $L_{3N}\ldots L_{B8}$¶ . Based on the design type and design variables, experiment design options were created. Each option is a set of input parameters for numerical simulation. The description of what was done to obtain the "experimental results" from the VAT based laminar or turbulent transport sets of equations for flow in a specific porous media is decribed elsewhere (see Travkin and Catton, 1995; Travkin et al., 1998).

We applied to the multiparameter optimization problem the method of design of experiments (DOE) (Travkin et al., 2000,2001a) for the morphology of round pin fin HS, Figure 15.

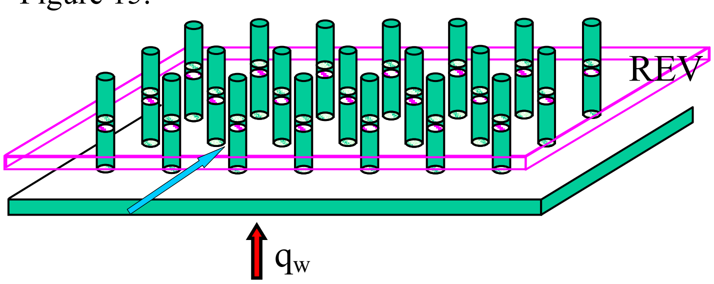

Figure 15 Pin Fin Heat Sink Morphology Model

Fig. 16 shows heat sink optimization algorithm using VAT theory and statistical tools. To address the issue of heat sink optimization, firstly, one needs to find the constraints of optimization and the variables for optimizations. Some possible constraints are the limit of the total volume Ω, the limit of the maximum temperature incensement, $(T_{w,max} - T_{in})$ and the limit of the maximum pumping power consumption P_p. Generally the optimization variables for pin fin heat sink optimization are heat sink base thickness t, heat sink material conductivity k_s , pin fin pitch P, pin fin height *H*, pin fin diameter d_p, heat sink base area *L*L*, and flow Reynolds Re_{por}. Secondly, one needs to estimate the range of those optimization variables. Then, to calculate the range of those optimization control variables listed in tables for laminar and turbulent regimes. Thirdly, generate numerical simulation cases using statistical tools. Next, calculate the goal of optimization, E_{eff}, through numerical simulation. Finally, statistically analyze the numerical results for optimization response surface.

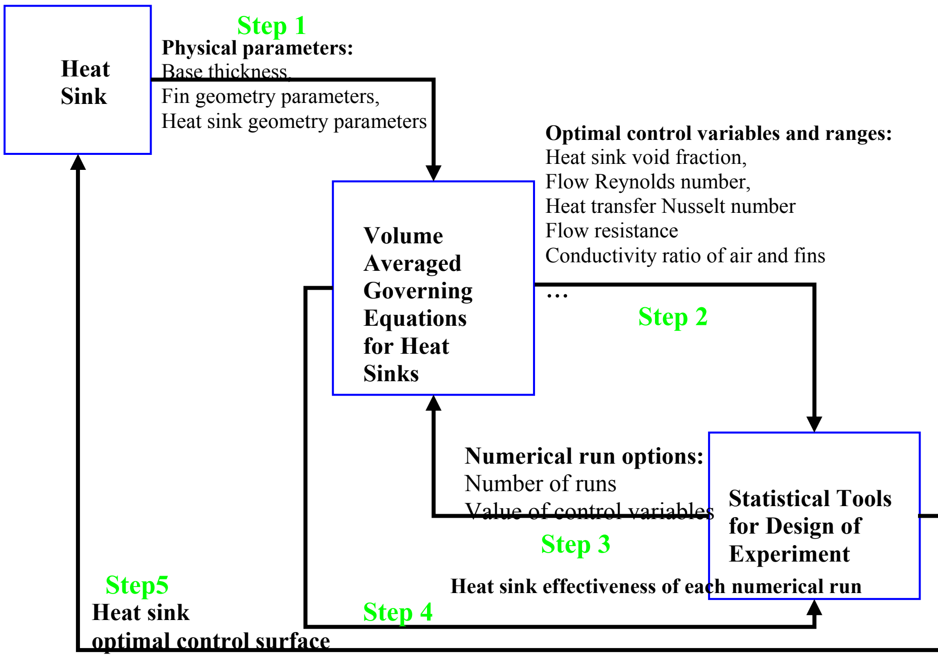

Figure 16 Pin Fin Heat Sink Morphology Model

Figures 17 and 18 clearly demonstrate an optimum value of E_{eff3}. When the porosity is higher than some critical value, the porous media play a more important role in increasing the heat transfer than in increasing the drag resistance. But when the porosity is too low, the drag resistance will be high and E_{eff3} will approach 0 when the porosity approaches zero.

For pin fin heat sink optimization, table shows a case of optimization. Figure 19 and Figure 20 show two examples of the heat sink heterogeneous effectiveness response surfaces. The three dimensional figure shows E_{eff1} as a function of two variables L_{P2} and L_{M4} (these were chosen for simplicity from the eight independent variables analyzed) when the other variables are fixed.

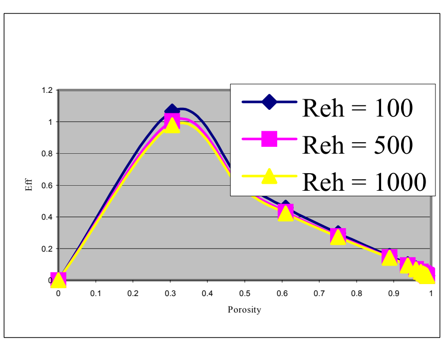

Figure 17 Channel Effective Number Versus Porosity for Flow Across Square Rod Banks

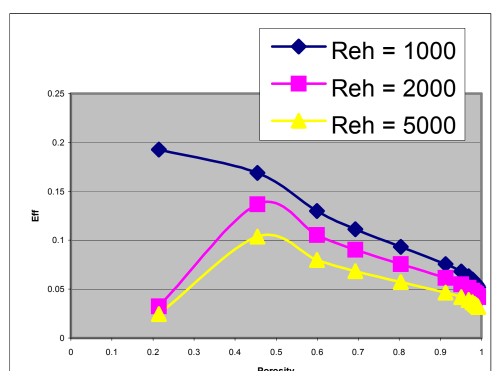

Figure 18 Channel Effective Number Versus Porosity for Flow Across Circular Pin Fins

Although limited by the range of the variables, the optimum point is shown on the figure and the trend of the response surface clearly shown in Figure 19.

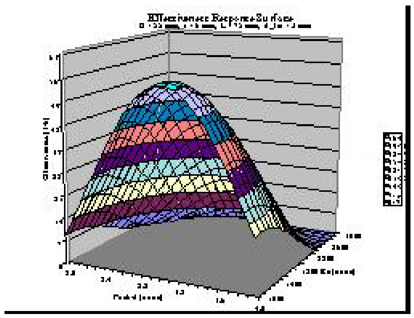

Figure 19 Heat Sink Optimization Response Surface for Changing Fin Pitch and Channel Re Number

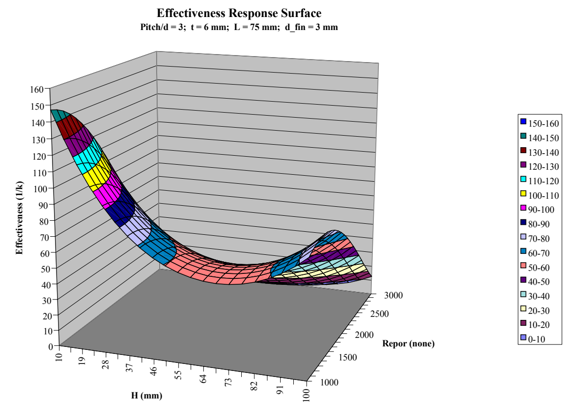

Figure 20 Heat Sink Optimization Response Surface for Changing Fin Height and Re Number

2.11 Accomplished Sub-Tasks

1) Has been developed heterogeneous two and three scale volume averaging theory (VAT) semiconductor heat sink (SHS) models and mathematical methods for closure of heterogeneous terms in optimization governing equations. Simulated few canonical and test morphology designs on the lower level of heat transport modeling.

2) The new approach to experimental science with regard to heterogeneous multi-scaled media was developed. The approach has appeared as a logical consequence of application of the VAT to the description and understanding of the experimental methods in heterogeneous media, such as solid foams, which were under our investigation in a number of years.

3) Developed methodologies for optimization of simplified regular medium SHS based on statistical design of experiments (DOE) approach. Ran the simulation experiments and obtained preliminary results.

4) Obtained the results which allow to support the statement about achievable the absolute upper limit of heat dissipation heat transfer rate and effectiveness on the upper scale of SHS in brackets of accepted physical phenomena and in outlined morphological class as, for example: a) 2D longitudinal or transverse regular rib fins; or b) 3D transversely (cross flow) streamlined regularly located circular cross section and arbitrary located in 2D (x,z) pin fins; or c) 3D arbitrary shape regularly located pin fins.

5) The Two-Scale Modeling Based Results: The scaled VAT formulation allowed to include and highlight the phenomena and features those are even not available to observe and they are not included into the conventional homogeneous simulating models. As among others: a) the surficial transport (might take few percent of the overall rate), interface transport with exact description of its values via the morphology influence (might be in a range of 20 % and more); b) interfield's based heat transport (as driven by

fluctuations in temperature and in fluid velocity, for example) might comprise the value of ~10 %; c) nonlinearities in physical models and their coefficients interacting one with another, etc.; d) the VAT based heat sink heat transfer parameters are vector and tensor variables tied directly to the each phase performance; e) the method of two-scale design of SHS has been suggested, and demonstrated features of this method.

2.12 Conclusions

1) In our efforts to relate the scaled volume average theory (VAT) description and simulation of semiconductor heat sinks heat transfer (heat-sink-to-air) to experimental measurements, we developed a process of coupling two scale Detailed Micro-Modeling - Direct Numerical Modeling (DMM-DNM) and their corresponding experimental results for a heat sink design. The two scale VAT description equations applicable to the problem have four additional descriptive terms in the momentum equation (for the 1D turbulent equation), seven terms in the fluid temperature equation, and five additional terms in the solid phase (reflecting heat transport through ribs, pins) temperature equations. These additional terms provide far more information about the heat sink and its design than the usual homogeneous models

Most of the additional terms in the VAT equations are terms which based on effects of interface phenomena and field fluctuations acting in the phase. There is, however, a lack of experimental results and data reduction procedures particularly developed for the purpose of experimental closure or verification of VAT heat exchanger governing equations. Contrary to a numerical simulation experiment, the physical experiment is usually much more restrictive in terms of the number and location of local experimental points. It is a problem to properly relate the available local measurements to VAT closure and to measurements within the volume of the heat exchanger. The measurement set-ups were designed and the local and bulk variables data assessed experimentally. The simulation methods using the CFD PHOENICS software along with the custom developed computational subroutines and user interface were designed and implemented in the study.

It was described in detail how, and for what reasons, the data are to be simulated or measured and represented in a way that allows design goals to be formulated primarily with bulk physical characteristics. Different techniques and models were studied for the four sample semiconductor heat sinks of two morphologies. There were changes in by-pass values, external heat flux and flow rate. The results are depicted with using new parameters that better represent the needs of a design process as well as the usual parameters used in the past. Characteristics reported for the first time are the heat transfer rate in solid phase, relative fluid phase and fin effectiveness, and influence of only morphology features among others.

2) There are a number of traditional techniques applied to the optimization of heat transfer devices such as heat sink enhanced surfaces or heat exchangers. There are, however, no methods or mathematical studies devoted to optimization of hierarchical heat transfer devices. Design 0f optimization procedures for transport in porous structures and enhanced heat transfer surfaces are formulated and developed in this study for the purpose of hierarchical heat sink design. Mathematical formulation of a hypothetical heat transfer surface with a priori unknown heat transfer enhancing elements is developed

using a two-scale description based on volume averaging theory (VAT). Second order turbulent model equation sets based on VAT are used to determine turbulent transport and two temperature diffusion in a non-isotropic porous media and inter-phase exchange at a rough wall. Though several different closure models for the source terms for spatial uniform, non-uniform, non-isotropic highly porous layers have been successfully developed, quite different situations arise when attempting to describe processes occurring in irregular, random or even unknown morphologies. A two-scale heterogeneous heat transfer optimization problem can be solved using exact procedures for closure of additional differential and integral VAT terms. For more complex or even unknown morphologies as initial spatial morphologies, the mathematical methods were outlined in detail. After simplification by assuming regularity of the spacial morphology, this problem is still has a large number of optimization space dimensions. In a laminar heat transfer region, the problem is 6 to 8-D and in turbulent it is 8 to 9-D.

It's been illustrated a method of hierarchical optimization of two- and three scale heat transport in a heterogeneous media of a semiconductor heat sink. It is shown how traditional governing equations developed using rigorous VAT methods can be used to optimize surface transport processes in support of heat transport technology. The problems in treating a multiple optimization parameter (more than 3) problem, even linear, are known to be very difficult to overcome using a parameter sorting process. The combination of VAT based equations and the theory of statistical design was used to effectively begin treating 6D or 8D optimization problems for the design of SHS.

3 List of Publications

1. Catton, I., Hu, K., and Travkin, V.S., ``Optimal Design of Heat Rejection Devices," in Proc. THERMINIC'2001, Paris, France, pp. 136-141, 2001.
2. Rizzi, M., Canino, M., Hu, K., Jones, S., Travkin, V.S., and Catton, I., "Experimental Investigation of Pin Fin Heat Sink Effectiveness," in Proc. NHTC'01, 35th National Heat Transfer Conference}, ASME, Anaheim, CA, 2001.
3. Travkin, V.S., Catton, I., and Hu, K., "Optimization of Heat Transfer Effectiveness in Heterogeneous Media," in Proc. Eighteenth Symposium on Energy Engineering Sciences, Argonne National Laboratory, 2000.
4. Travkin, V.S., "Relating Semiconductor Heat Sink Local and Non-Local Experimental and Simulation Data to Upper Scale Design Goals," in Intern. Mech. Engin. Congress and Exposition (IMECE'2001), IMECE/HTD-24383, pp.1-12, 2001.
5. Travkin, V.S., Hu, K., Rizzi, M., Canino, M., and Catton, I., "Revising the Goals and Means for the Base-to-Air Cooling Stage for Semiconductor Heat Removal - Experiments and Their Results," in Proc. 17th IEEE SEMI-THERM Symp., pp. 85-94, 2001a.
6. Travkin, V.S., Hu, K., and Catton, I., "Multi-variant Optimization in Semiconductor Heat Sink Design," in Proc. NHTC'01, 35th National Heat Transfer Conference, ASME, Anaheim, CA, 2001b.

7. Travkin, V.S., Sergievsky, E.D., Krinitsky, E.V., and Catton, I., "Integrated Heterogeneous Design of Semiconductor Heat Sink via Scaled Direct Micro-Modeling, Upper Scale VAT Simulation and Experiment. Comparison and Verification of Properties," in Intern. Mech. Engin. Congress and Exposition (IMECE'2001), IMECE/HTD-24380, pp.1-6, 2001c.

8. Travkin, V.S., Hu, K., and Catton, I., "Exact Closure of Hierarchical VAT Capillary Thermo-Convective Problem for Turbulent and Laminar Regimes," in Intern. Mech. Engin. Congress and Exposition (IMECE'2001), IMECE/HTD-24261, pp.1-12, 2001d.

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