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Application of Computational Fluids Dynamics (CFD) Analysis to the Thermal Design of Electronic Equipment - Modeling Methodologies, Capabilities and Limitations

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Introduction

To satisfy consumer demands for more compact and sophisticated electronic devices, advances of semiconductor technology have achieved increased Integrated Circuit (IC) functionality and miniaturisation. However, the continuous increase of both switching speed and transistor density, still described by Moore's law, have inadvertently resulted in rising die heat fluxes, which, if not efficiently removed from the device, may impact on product performance and reliability. While no generic relationship exists to relate component and Printed Circuit Board (PCB) temperature with reliability, it has been shown that die circuit performance can be highly sensitive to operating temperature, and therefore temperature must be controlled.

This need, combined with shortening product design cycle times and the demand for more reliable electronic systems, has heightened the requirement for innovative thermal design methods that enable accurate solutions to be generated and quickly assessed. Over the last decade, design practices have progressed from basic analytical and semi-empirical calculations, applicable to simple systems, in tandem with extensive physical prototype characterization, to a high reliance on virtual prototyping using numerical predictive techniques. Their application, now widespread within the electronics industry, has been enabled by increases in computational power, and contributed to significantly reduce both prototyping costs and development cycle times. The use of Computational Fluids Dynamics (CFD)-based methods that simultaneously solve the appropriate governing equations for the solid and fluid domains, and couple both at the solid-fluid interface, is the most realistic approach for the prediction of conjugate heat transfer in electronic equipment.

The onus is on the CFD user to employ both the correct modelling strategy and flow modelling approach for the application under analysis. To optimise the potential of CFD analysis, many factors need to be taken into consideration which impact on predictive accuracy, namely; computational constraints, uncertainties in physical boundary conditions, numerical modelling simplifications, and inherent limitations in the code numerics and turbulence modelling. In this context, depending solely on CFD predictions without supporting experimentation still remains an unreliable design strategy, and an efficient approach therefore requires a balanced combination of both experimental and numerical efforts. This course provides guidance on optimising the application of CFD analysis to electronic system thermal design, from the selection of a cooling strategy, refinement of the thermal design by parametric analysis, to providing perspective on the use of temperature predictions as critical boundary conditions in electrical performance- and thermo-mechanical behaviour analyses, and reliability calculations.

Course objectives

This course provides numerical modelling strategies and methodologies for the thermal design of electronic equipment, which are generically applicable with CFD codes dedicated to the thermal analysis of electronic systems. The course also permits an understanding of the technical capabilities and limitations of CFD analysis at the various phases of the product design cycle to be gained. Practical application examples are presented for the analysis of system-, board- and component level heat transfer. The course has no bias towards a particular CFD code.

Who should attend?

The course will benefit engineers, managers and scientists involved in the thermal management of electronic systems. It is aimed at participants with varying expertise levels in CFD, from novice to advanced.

Course description

This one-day course focuses on the application of CFD analysis to electronic system thermal design, and is structured as follows:

In Section 1, the evolution of thermal design practices within the electronics industry is summarised, from the use of combined empirical data (Nusselt-number based correlations) and analytical techniques, electro-thermal analogue representations based on thermal resistance network methods, numerical schemes solving conductive heat transfer problems with prescribed convective and radiative heat transfer boundary conditions, to CFD-based methods solving conjugate heat transfer problems. The predictive accuracy requirements that CFD analysis must meet throughout the various phases of the thermal design process to minimise the extent of physical prototyping are outlined, from the selection of a thermal management strategy, refinement of the thermal design, to the prediction of critical temperature boundary conditions for use in life-cycle costing, reliability calculations, electrical performance and thermo-mechanical behaviour analyses.

In Section 2, the governing equations that are simultaneously solved by CFD analysis for the solid and fluid domains are described. Turbulent flow modelling approaches are outlined. The main features of the computational methods employed in CFD codes dedicated for the thermal analysis of electronic equipment are presented. Their capabilities for the analysis of electronics cooling, and more specifically board-mounted electronics are discussed.

In Section 3, the implementation of an effective thermal analysis strategy focusing at all hierarchical levels of the heat transfer chain in an electronic system, from component acting as thermal 'source', to the external environment acting as 'sink' is described. The impact of both computational constraints, prohibiting detailed geometry modelling, and uncertainties in both physical quantities and applied numerical boundary conditions on predictive accuracy is discussed. Methodologies are outlined for system-level modelling of components, boards, fans, vents, grilles to permit extraction of boundary conditions for subsequent detailed board-level analysis.

Section 4 focuses on board-level analysis. Methodologies are presented for component and printed circuit board modelling, with both detailed and compact approaches reviewed. Current component packaging technologies are covered. The specification of thermo-physical properties is outlined. Computational domain construction, and prescription of system-level boundary conditions are described. Construction of the computational grid for the fluid and solid domains is described, for both natural convection and forced air-cooled applications, laminar and turbulent flow regimes, and both structured and non-structured grid systems. Fluid flow modelling is discussed in the context of a typical thermal design scenario, where in the absence of a physical prototype the CFD user may have no a priori knowledge of the flow regime, and whether it is steady or unsteady. Laminar versus turbulent flow model selection is examined in the above context, that is with the problematic definition of a dominant characteristic length scale to describe the flow regime in non-dimensional form. The applicability of different flow models, including near-wall treatment approaches, to the analysis of populated board heat transfer is discussed. The impacts of fluid flow conditions, component thermal interaction on densely populated boards, and uncertainties in physical boundary conditions on predictive accuracy are both quantitatively and qualitatively discussed.

In Section 5, the design methodologies previously presented are applied to the analysis of several air-cooled electronic applications spanning from component- to system level. Both natural- and forced convection environments are considered. The appropriateness of the modelling methodologies employed is demonstrated by comparing numerical predictions with experimental measurements for validation test cases, having well-defined boundary conditions. Predictive accuracy for more complex applications is then quantitatively assessed, and sources of predictive discrepancies discussed. The use of flow visualisation on mock-up prototypes to identify aerodynamically sensitive regions is presented, so as to stress the need for cautious consideration of temperature predictions in these regions. To illustrate this, practical instances are shown where the use of a single flow model is not sufficient to permit accurate prediction of component operating temperature throughout the system.

In Section 6, important aspects of the course are summarised, with rules-of-thumb given for the successful application of CFD to the analysis of electronic equipment heat transfer.

Course outline

1. Thermal design methods for electronics cooling

- Physical prototyping
- Predictive methods
  - Analytical, semi-empirical, resistive networks, numerical
- CFD analysis
  - Predictive accuracy requirements throughout the various phases of the thermal design process

2. CFD fundamentals

- Governing equations
- Turbulence modelling
- Code numerics
  - Discretization scheme, algorithm scheme, equation solver
- Inherent limitations for the thermal analysis of electronic equipment

3. System-level modelling

- Heat transfer chain
- Computational constraints
- Modelling methodologies
  - Components, boards, grilles, vents, fans
- Extraction of board-level boundary conditions

4. Board-level modelling

- Component and PCB modelling
  - Geometry
  - Thermo-physical properties
- Computational domain
  - Implementation of system-level boundary conditions
- Grid discretization
- Fluid flow modelling
- Factors impacting on prediction accuracy for component- and board operating temperatures
  - Fluid flow conditions
  - Component thermal interaction
  - Uncertainties in physical boundary conditions

5. Case studies for the analysis of electronic equipment heat transfer

- Applications and test vehicles
- Experimental measurements
  - Component junction temperature
  - Component-PCB surface temperature
  - Fluid flow field visualisation and measurement
- Numerical models
- Predictive discrepancies with measurements

6. Summary and discussions

Instructor

Dr. Peter Rodgers is director of Electronics Thermal Management Ltd., a research and consulting firm specialized in electronics cooling. He holds a Ph.D. degree in mechanical engineering from the University of Limerick, Ireland and has been involved in electronics thermal management for thirteen years. Dr. Rodgers was formerly with the Nokia Research Center, Finland, where he consulted on electronics thermal management within the corporation, and lead a research programme on benchmarking the predictive accuracy of CFD codes dedicated to the thermal analysis of electronic equipment. For publications associated with this work, he was awarded the 1999 Harvey Rosten Award for Excellence. Dr. Rodgers is a member of the EuroSIME, SEMI-THERM and THERMINIC conference programme committees, and has been an invited lecturer, keynote speaker and panelist to discussions on simulation issues in electronics thermal management at international conferences. He has authored or co-authored over thirty refereed conference and journal publications. He is currently supervising doctoral research on the application of CFD analysis to electronics thermal design, undertaken at Electronics Thermal Management.