Thermal Management of Electronic Systems : Emerging Technologies and Acoustic Challenges

Gestion thermique des systèmes électroniques : Technologies naissantes et défis acoustiques

Jeff Punch
CTVR
Stokes Institute
University of Limerick
Limerick
IRLANDE
Tel. : +353 61 213004
Fax : +353 61 202393
E-mail : jeff.punch@ul.ie

Summary
This paper addresses a range of emerging cooling technologies for electronic systems which are deployed at the location of power generation – in contrast with conventional forced convection schemes which predominantly involve heat sinks cooled using fans. A set of these 'point-of-source' technologies are outlined, ranging from small-scale air movers and microchannel coolers, to heat pipes and thermoacoustic engines. Recent research at the author's Institute into two point-of-source thermal management solutions is reviewed: micro fans; and microchannel coolers. Energy aspects of point-of-source cooling technologies are considered, with specific reference to the opportunities for efficient cooling schemes associated with low thermal resistance paths from source to sink. Finally, three challenges in thermal management for the acoustics community are outlined: noise minimisation; simulation; and the application of thermoacoustic phenomena.

Résumé
Cet article présente une toute nouvelle gamme de technologies de refroidissement pour systèmes électroniques dont l'utilisation s'effectue directement à la source électrique – contrairement aux agencements conventionnels de type convection forcée qui impliquent principalement des radiateurs refroidis à l'aide de ventilateurs. Un ensemble de ces technologies de «point-de-source» sont décrits, depuis de petits moteurs à air et refroidisseurs basés sur l'utilisation de micro-canaux, jusqu'aux caloducs et autres moteurs thermo-acoustiques. De récentes recherches portant sur deux solutions de gestion thermique de «point de source» et développées au Stokes Institute sont passées en revue : les micro-ventilateurs et les refroidisseurs utilisant de micro canaux. L'aspect énergétique de ces technologies de refroidissement «point de source» est considéré, avec une référence particulière sur la possibilité d'obtenir des refroidisseurs efficaces associés à de faibles résistances thermiques entre source et drain. Enfin, trois défis dans la gestion thermique pour la communauté acoustique sont décrits: minimisation de bruit; simulations; et application des phénomènes thermo-acoustiques.

Consumer demand for smaller products with more functions, coupled with advances in microelectronic integration, has driven the miniaturisation of electronic devices over the past three decades. Thermal management has become a critical issue in product design, however, due to increasing power dissipation levels and decreasing space available for cooling solutions. Components must be maintained below temperatures (~100°C) which are critical for performance and reliability. Heat is ultimately rejected to the ambient air (~0-50°C), and it is customary to define thermal resistance as a measure of heat transfer from source to sink. For heat dissipation, Q (W), from a silicon junction at temperature, Tj (°C), to ambient at temperature, Ta (°C), thermal resistance, Rth, is defined as (1):

$$R_{th} = \left(\frac{T_j - T_a}{Q} \right)$$

Power dissipation for microprocessors in contemporary server applications is over 100W, and the design value of thermal resistance is ~0.1°C/W. Most of today's thermal management solutions use air as the cooling medium, utilising heat sinks and fans to overcome the high thermal resistances associated with convective heat transfer. Cooling solutions must also be capable of removing very high heat fluxes – at component level, heat flux is now over 50 W/cm2 – and this is on the limit of conventional air cooling. Although there has been recent discussion about extending the performance of air cooling – Rodgers et al [1], in particular – it is clear that the adaptation of liquid cooling is imminent for many high power applications due to increasing heat flux levels at die, package and substrate.

The theme of this paper is the emerging thermal management techniques which act directly at the location of power generation within electronic systems. These so-called point-of-source technologies can be categorised in contrast with conventional forced convection cooling schemes – see figure 1 – which predominantly achieve local energy removal using heat sinks, utilising system-level airflow as the medium for heat transfer.

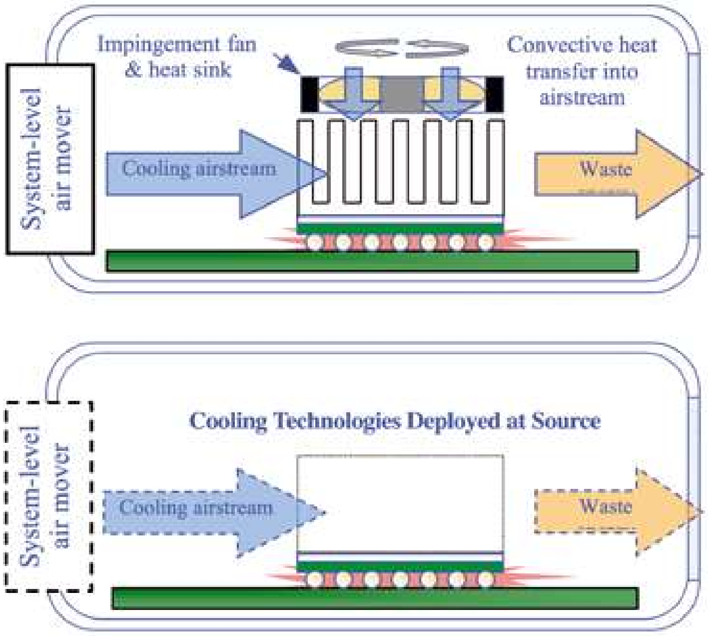

Fig. 1: Thermal management: conventional air cooling and point-of-source technologies

Conventional schemes offer many advantages – cost, flexibility, no limitations in terms of cooling fluid – however a penalty is incurred due to relatively high thermal resistances from the source to the ultimate energy sink. Cooling technologies deployed at source can offer enhanced thermal performance. Some examples are as follows:

Small-scale air movers : Rotary or oscillatory devices have been reported in the literature. Microfans are covered in detail in this paper, and oscillatory fans driven by piezoelectric actuators have been developed – for example, Burmann et al [2]. These small-scale air movers can be used to enhance local heat transfer rates, as package-level coolers, or to act as system-level fans for portable devices.

Microjets/microspray : A number of authors have reported microjets for chip-level liquid cooling – Wang et al [3], for example. Micro-spray nozzles generate 50-100mm droplets of a dielectric fluid which, impinging on the textured back surface of a chip, can remove fluxes of over 100 W/cm2.
Heat pipes: Numerous references cite the development of micro-scale heat pipes – Lee et al [4], for example. Micro-scale hydraulic diameters have been realised, with modest power densities. Contemporary research is addressing microfabricated structures to enhance capillary pressure, and the integration of heat pipes in silicon, Gillot et al [5].

Microchannel coolers : The formation of channels in silicon to facilitate liquid cooling dates back to the early 1980's, however widespread application is not yet evident. High heat fluxes – of order 103 W/cm2 – are feasible, yet a number of practical impediments remain – in particular related to pumping requirements. Microchannel characteristics are reported in this paper. With reference to liquid-cooled cold-plates, Garimella et al [6] note the evolution of meso-scale components as an enabler for smaller scale devices.

Thermoacoustic cooling : The adaptation of thermoacoustic engines for thermal management has been made feasible by today's microfabrication techniques. A high-frequency – 4 to 24 kHz – thermoacoustic device for electronics cooling is reported by Symko et al [7]. Operation as both acoustic cooler and prime mover is described, and avenues for further improvement – specifically smaller scale, higher frequency – are discussed in Abdel-Rahman et al [8].

Micro thermoelectric cells : Small scale thermoelectric cells have been realised – daSilva and Kaviany [9], for example. Thermoelectric cells are more suitable for thermal control than for cooling, however, due to their high thermal resistance, high current requirement, and low coefficient of performance.

A key feature of these point-of-source technologies is that their deployment has generally been facilitated by recent advances in micro-manufacturing. Micro-fabrication techniques such as surface and bulk silicon micromachining, laser micromachining, polymer micro-embossing and Electro-Discharge Machining (EDM) have enabled the creation of the small scale (~100mm) features at the core of these technologies; moreover, surface structuring has allowed the enhancement of effective area, and the control of parameters such as radiation properties, friction factor and – for objects in contact – thermal interface resistance. Contemporary development of microfabrication is particularly vibrant, offering rich possibilities for the further evolution of thermal management technologies.

The next sections of this paper cover some point-of-source thermal management solutions under investigation at the author's Institute. Energy aspects of point-of-source cooling technologies are then considered, with specific reference to their sink temperatures. In the context of large-scale electronic systems, heat transfer paths from source to sink with greatly reduced thermal resistance open opportunities for efficient cooling schemes or – potentially – the recovery of energy. Finally, the paper outlines three challenges in thermal management for the acoustics community: the minimisation of noise from sources such as fans and hard disk drives; the simulation of acoustic noise in electronic systems; and the application of thermoacoustic phenomena.

Thermal Management Solutions

This section comprises a review of recent research at the Stokes Institute into point-of-source thermal management solutions: small-scale fans; and microchannel coolers.

Small-scale fans

A programme of research is in progress at Stokes on the design, fabrication and performance characterisation of small-scale fans for thermal management. Two main application areas are envisaged: product-level cooling for portable electronic devices; and package-level cooling for a range of electronic systems. For the latter applications, integration of the fan with the package is proposed in order to achieve heat removal at source.

A key challenge in the development of small-scale fans is the reduction of efficiency with scale, a limitation of turbomachinery at low Reynolds numbers. In order to assess this phenomenon, a set of three geometrically-similar axial flow fans was created, based on a 120mm diameter fan – full scale, 1/3rd scale and 1/20th scale. The 6mm diameter fan shown in figure 2 – from Grimes et al [10] – was fabricated using a micro Electro Discharge Machining (mEDM) process, and driven by a brushless DC micro-motor.

Fig. 2 : 6mm diameter axial microfan

Pressure-flow characterisation tests were performed on the three fans at 0.049 specific speed in order to compare their performance. To maintain this specific speed, the full scale, 1/3rd scale and 1/20th scale fans were tested at 2,240rpm, 6,720rpm and 44,800rpm respectively.

Figure 3, from Grimes et al [11], shows non-dimensional static pressure rise for the three fans. Characteristics of the full scale and 1/3rd scale fans are similar, but the performance of the 1/20th scale fan is lower in terms of both pressure and flow rate – a difference attributed to inaccuracies in scaling tip clearance. In dimensional terms, maximum volumetric flow rate of the 6mm diameter fan is 0.263 m3/hr, a delivery which yields an average velocity of 3-4 m/s at outlet. The physical scale of this fan is suitable for integration into portable devices, and the volumetric flow rate is sufficient to achieve system-level heat removal. Moreover, the delivery velocity is adequate to enhance package-level cooling – particularly in conjunction with extended surfaces.

Particle-Image Velocimetry (PIV) was also performed on the full scale and 1/3rd scale fans in order to investigate the influence of scale on the exit flow field. Two specific speeds (0.049 and 0.061) and five pressure rises (0, 5, 10, 15, and 20 Pa) were assessed, and a sub-set of the results – from Quin et al [12] – is presented in figure 4. For these results, the full scale and 1/3rd scale fans were run at 2,800 rpm and 8,400 rpm respectively in order to achieve a specific speed of 0.061. Two pressure rises – 0 Pa and 20 Pa – are featured in order to illustrate the range of flow behaviour from maximum delivery to maximum pressure.

At zero pressure – maximum delivery – the flow from the full scale fan is predominantly axial, with some divergence into the dead zones in front of the fan hub and blade tip. An increase in pressure induces partially radial flow in the full scale fan, the influence of changing centripetal forces in the jet due to an increase in tangential flow. The flow from the 1/3rd scale fan has significant radial components even with zero pressure rise. Magnitudes of the velocity vectors are lower than for the full scale fan, and more air recirculates in front of the fan hub: these phenomena are more strongly evident at higher pressure.

It is clear that the flow from small scale axial fans is significantly radial in character: there would appear to be advantages in

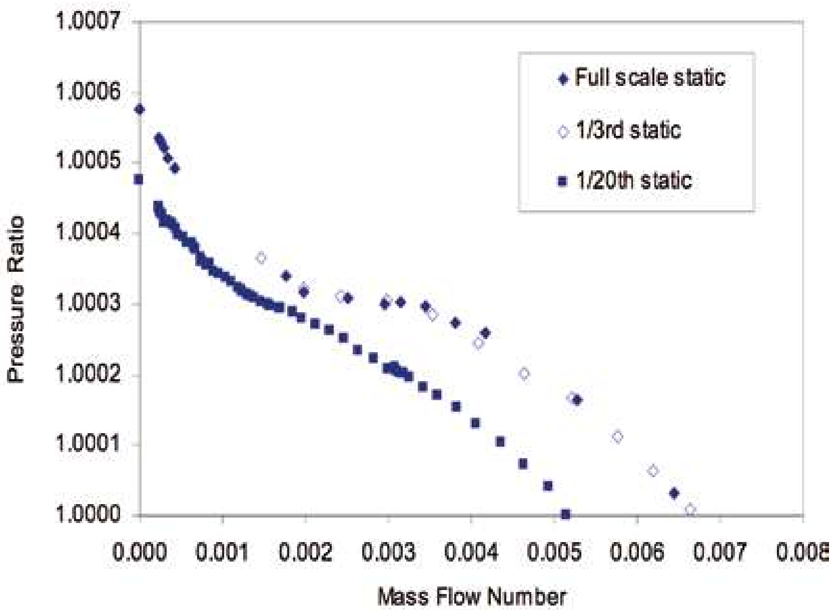

Fig. 3 : Non-dimensional fan characteristics for 0.049 specific speed

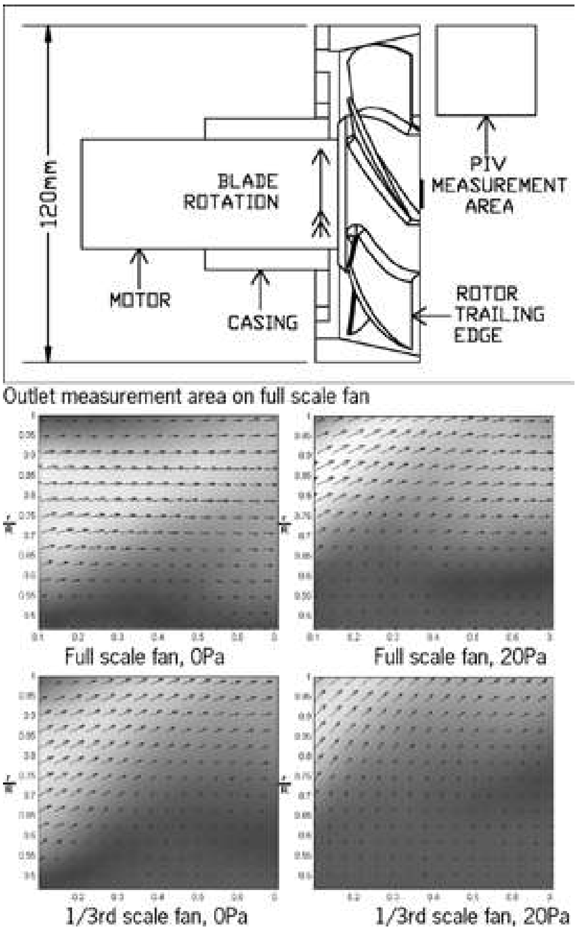

Fig. 4 : Outlet axial and radial flow vectors, full scale and 1/3rd scale axial fans at 0.061 specific speed

a scrolled radial configuration. Consequently, a range of scaled radial microfans has been designed and fabricated at Stokes. Initial characterisation results demonstrate superior performance characteristics to equivalent axial microfans.

Microchannel coolers

The Stokes Institute, in conjunction with the Tyndall Institute in Ireland, have successfully produced relatively large microchannels – hydraulic diameters from 255 to 317µm – in thermoset plastic and silicon using three different methods: Precision Sawing, Deep Reactive Ion Etching (DRIE) and Wet Etching. Mechanical sawing produced near rectangular channels in two types of thermoset plastic, with SU-8 photoresist used as an adhesive to bond glass covers over the channels. Glass covers were anodically bonded over the DRIE and Wet Etched silicon channels. Full fabrication details are presented in Eason et al [13], and sections of the channels are illustrated in figure 5.

Eason et al [14] describes a modular system for testing each sample using identical inlet and outlet manifolds, pressure tappings, pumping system, temperature sensors and instrumentation. The channels – occupying a 16×30mm area array – were tested using the same inlet and outlet manifolds. Figure 6 shows measured pressure flow and heat transfer behaviour for the channels, with other reported data from the literature. Comparisons with theoretical values, as calculated from macro scale theory, were also drawn. Heat transfer data from the channels correlates well with literature given that entrance effects are ignored in the comparison. Predicted pressure drops were also found to compare well to experimental values with no deviation from classical hydrodynamics theory outside a 95% confidence interval (see Fig. 6 next page).

A key challenge in the practical implementation of microchannel coolers is the pumping of the fluid, specifically due to the high pressure drop associated with the channels. Garimella and Singhal [15] indicate that valveless, piezoelectric and electroosmotic pumps appear to be most appropriate for thermal management applications. Contemporary developments in surface coatings may offer opportunities to enhance the performance of microchannel coolers, moreover, specifically through a reduction in pressure drop. In this regard, Stokes are currently collaborating with Bell Laboratories on the adaptation of nano-structured surfaces – as described in Krupenkin et al [16] – to microchannel geometries in order to provide control of hydrophobicity and pressure drop.

Energy Considerations

The thermal management of today's large scale electronic systems represents a substantial energy cost. Shah et al [17] indicate power densities of over 3kW/m2 for data centres within 3 years, outlining a 10,000m2 centre containing five thousand 10kW computing racks which could feature power dissipation of order 50MW. A conventional air conditioning cooling scheme would consume an extra 20 MW which, at an assumed energy cost of \$100/MWh, would incur \$18 million per annum for cooling alone. Moreover, concerns have been expressed with reference to sustainability aspects of thermal management: Bar-Cohen and Iyengar [18] adapted a 'least energy' approach to the optimisation of air cooled heat sinks which considers not only thermal performance, but also energy consumption associated with material extraction and fabrication. There is clear

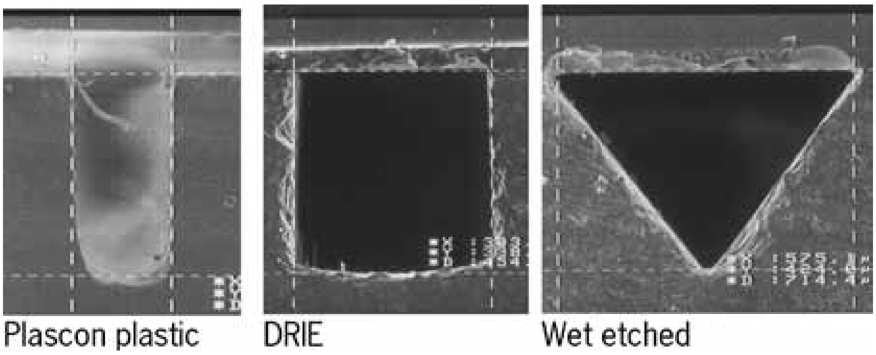

Fig. 5 : Microchannel geometries

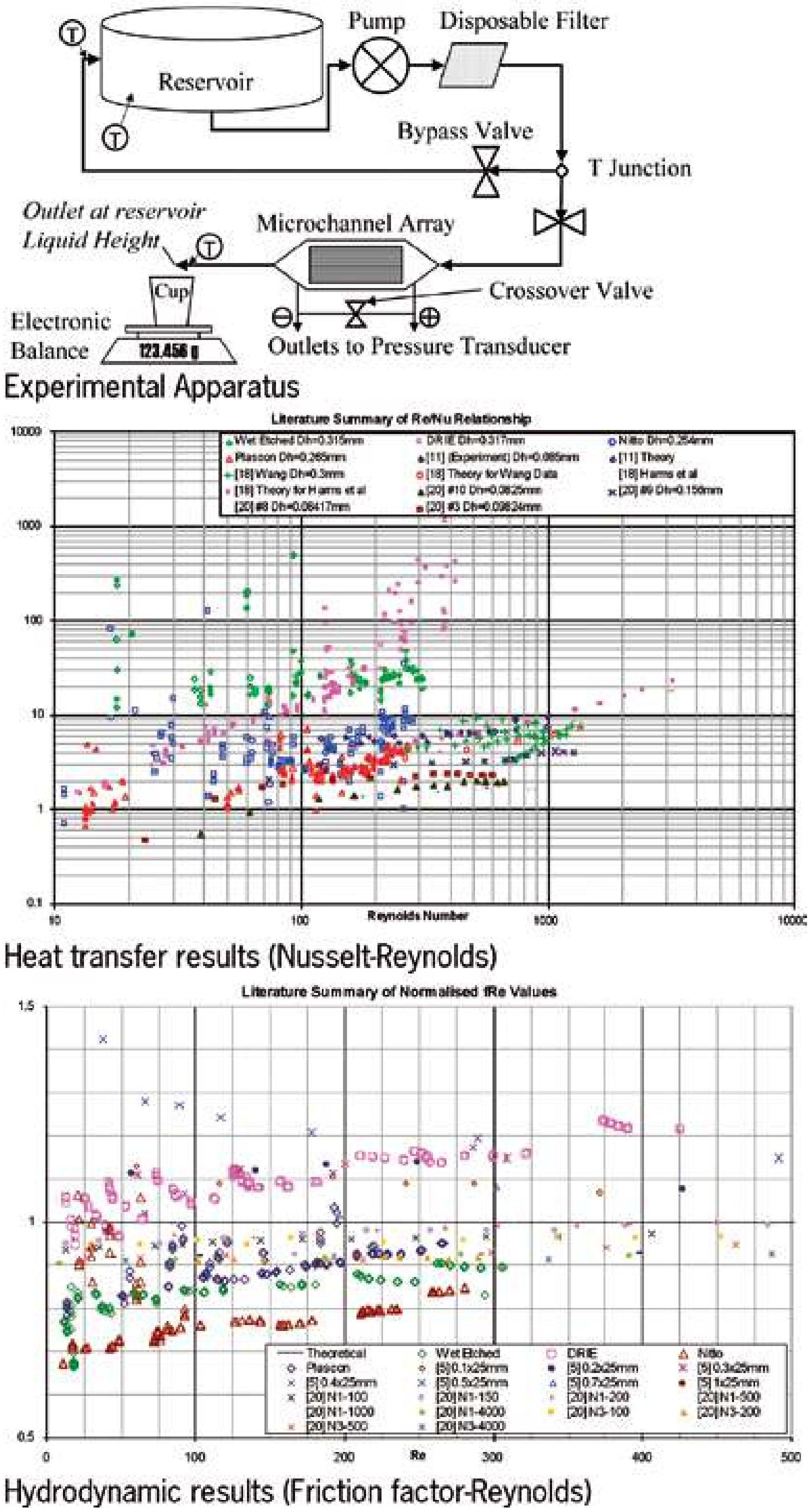

Fig. 6 : Comparison of heat transfer and hydrodynamic results with literature

evidence in the electronic packaging community that thermal management – with its focus on system reliability – is evolving to include energy management issues.

With reference to energy processing, point-of-source thermal management technologies open avenues for greater efficiency. By reducing thermal resistance from source to sink, higher sink temperatures are possible, potentially reducing the cost associated with removing heat to the ultimate energy sink – the ambient, external air. Moreover, the recovery of energy may even be feasible. Although it is not anticipated that sink temperatures would ever be sufficiently high to facilitate efficient thermodynamic engines, it may be possible to harness waste energy from an electronic system in order to drive the cooling scheme associated with the system. Solbrekken et al [19] illustrated this approach for implementation in portable electronics, using a thermoelectric cell to drive a cooling fan.

Portable systems are notably constrained in terms of available space, and it would appear that energy recovery in larger scale, fixed electronic systems – in data centres, for example – could offer large cost savings. In this regard, point-of-source thermal management technologies, by facilitating higher sink temperatures, may play a key role. For conventional air cooling, the waste energy stream is approximately 10-15°C above ambient: a thermal management solution with low thermal resistance which increased this temperature differential to 70°C would improve the thermodynamic (Carnot) efficiency from <5% to ~20%, which is possibly sufficient to contribute to running a cooling scheme.

Challenges for the Acoustics Community

Thermal management solutions which involve active element such as fans and pumps can generate appreciable levels of noise. Many applications are subject to stringent noise regulations – typically, sound power maxima of 4.5-4.8B and 5.0-5.5B, declared in accordance with ISO 9296, are stipulated for electronic equipment with fans in idle and operational modes respectively. As the power density of electronic systems increases, it will become necessary to deploy ever more aggressive cooling solutions – with higher speed fans, for example, or multiple fans – which will generate greater levels of noise. At present, it is generally the responsibility of thermal designers to manage acoustic noise – a task which is typically achieved through extensive testing of prototypes. It is evident that there is rich scope for acousticians to contribute to the application area of thermal management. In this regard, three challenges can be identified :

Minimisation of acoustic noise

In contemporary electronic systems, the main sources of acoustic noise are cooling fans and, to a lesser extent, hard disks. In high-power applications such as servers and telecommunications switches, the minimisation of noise generated by fans has become a critical challenge for designers – see Kaivola and Avikainen [20], for example.

The noise spectrum of a fan is typically broadband, but with strong peaks associated with bearings, vortex shedding from blades, and their harmonics. In addition, the spectrum varies as a function of rotational speed – the faster the speed, the louder the fan noise, and the stronger its distinct tones – and the operating point of the fan. In this regard, the higher the pressure differential across the fan, the higher the noise level. Fan manufacturers have made significant progress in creating quieter products but, nevertheless, it is usually necessary for designers to minimise noise through the use of speed control, for example, or the application of sound absorbent material. Extensive testing is customary because typical electronic systems are geometrically complex, and it is notably difficult to anticipate how sound may be amplified or attenuated by the structures and cavities of the system's cabinet. Moreover, the interaction of airflow with system features may generate specific tones, and multiple fans may create 'beating' effects. It is clear that acousticians can contribute through the formulation of design guidelines, and through the development of noise control techniques – the deployment of sound absorbent materials, for example, or active techniques for noise cancellation.

Simulation tools for acoustic noise

A range of simulation tools is available to assist with mechanical design aspects of electronic systems – computational fluid dynamics solvers for the thermal and airflow phenomena associated with cooling, and finite element packages for analysing mechanical and thermomechanical issues. There is no commercial simulation tool tailored for acoustic noise in electronic systems at present, however, and an opportunity is evident for a computationally-efficient, easy-to-use software package to support designers in dealing with acoustic phenomena. In this context, it is instructive to consider thermal simulation packages such as Flotherm which utilise 'compact models' in order to achieve easy model building and swift numerical convergence.
For example, perforated plates or filters – common features of electronic systems – are modelled simply as flow resistances using empirically-determined loss coefficients. In this manner, designers can select from a library of 'smart parts' such as fans, heat sinks, components and printed circuit boards in order to create a thermal model of an electronic system. A similar approach may be appropriate for an acoustic noise solver. In this regard, sources such as fans could be characterised in terms of noise level and spectral content, with 'compact models' used to represent the interaction of the acoustic field with structures such as circuit boards, heat sinks, perforated plates, filters and enclosures. It is also necessary, however, to consider noise generated by the interaction of airflow and system structures such as grilles or perforated plates. In this regard, mean air velocities in typical systems are low – of order 1-4m/s – but airflow is generally unsteady and spatially-varying, particularly downstream from cooling fans. There is much scope for applied research in identifying and implementing computationally-efficient modelling approaches for sound generation and propagation in electronic systems.

Thermoacoustic phenomena

Apart from vapour compression refrigeration for air chilling, there are some applications for heat pumps in contemporary electronic systems – in particular, thermoelectric modules based on Peltier cells are commonly used to achieve temperature control for photonic devices such as laser diodes. Thermoacoustic devices configured as acoustic coolers potentially offer advantages over heat pumping techniques such as vapour compression cycles or thermoelectric modules. Specifically, thermoacoustic devices feature low power consumption because their relative effectiveness is approximately twice that of thermoelectric cells. Moreover, they obviate the environmental threat associated with refrigerant fluids and, significantly, the simplicity of their structure offers the potential for low cost manufacture and high reliability. Finally, thermoacoustic devices configured as prime movers to dissipate heat in the form of sound could, for ultrasonic operation, facilitate point-of-source cooling for microelectronic devices – an intriguing, if difficult, possibility.
These three challenges – noise minimisation; simulation; and the application of thermoacoustic phenomena – offer rich opportunities for acousticians in the application area of thermal management.

Conclusions

A range of emerging point-of-source thermal management technologies has been outlined, from small-scale air movers and microchannel coolers, to heat pipes and thermoacoustic engines. Recent research at the Stokes Institute has been reviewed :
- Pressure-flow characteristics of a 6mm diameter axial fan have been presented, featuring a maximum delivery of 0.263 m3/hr, and mean outlet velocities of order 3-4 m/s. Small-scale radial fans are currently under development.
- The fabrication and performance characterisation of microchannels for package-level cooling has been reported. Relatively large channels – hydraulic diameters from 255 to 317µm – have been created in silicon and thermoset plastic. Pressure-flow characteristics and heat transfer data correlate well with classical theory for macro-scale geometries.

Energy aspects of point-of-source cooling technologies have also been considered, with specific reference to their sink temperatures. Heat dissipation paths with greatly reduced thermal resistance may facilitate efficient cooling schemes or – potentially – the recovery of energy to drive cooling systems. Finally, three challenges in thermal management have been outlined which represent opportunities for acousticians: noise minimisation; simulation; and the application of thermoacoustic phenomena.

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Bibliography

[1] Rodgers, P., Eveloy, V. and Pecht, M., 2005, "Extending the Limits of Air-Cooling in Microelectronic Equipment", (Keynote Presentation), Proceedings of the IEEE EuroSIME 2005, pp. 695-702

[2] Burmann, P., Raman, A. and Garimella, S.V., 2002, "Dynamics and Topology Optimization of Piezoelectric Fans", IEEE Transactions on Components and Packaging Technologies, Vol. 25, Issue 4, pp. 592-600

[3] Wang, E.N., Zhang, L., Jiang, L., Koo, J-M., Maveety, J.G., Sanchez, E.A., Goodson, K.E. and Kenny, T.W., 2004, "Micromachined Jets for Liquid Impingement Cooling of VLSI Chips Journal of Microelectromechanical Systems, Vol. 13 , Issue 5, pp. 833-842

[4] Lee, M., Wong, M. and Zohar, Y., 2003, "Characterization of an Integrated Micro Heat Pipe", Journal of Micromechanical Microengineering, Vol. 13, pp. 58-64

[5] Gillot, C., Avenas, Y., Cezac, N., Poupon, G., Schaeffer, C. and Fournier, E., 2003, "Silicon Heat Pipes Used as Thermal Spreaders", IEEE Transactions on Components and Packaging Technologies, Vol. 26, Issue 2, pp. 332-339

[6] Garimella, S.V., Joshi, Y.K., Bar-Cohen, A., Mahajan, R., Toh, K.C., Carey, V.P., Baelmans, M., Lohan, J., Sammakia, B. and Andros, F., 2002, "Thermal Challenges in Next Generation Electronic Systems - Summary of Panel Presentations and Discussions", IEEE Transactions on Components and Packaging Technologies, Vol. 25, Issue 4, pp. 569-575

[7] Symko, O.G., Abdel-Rahman, E., Kwon, Y.S., Emmi, M. and Behunin, R., 2004, "Design and Development of High-Frequency Thermoacoustic Engines for Thermal Management in Microelectronics", Microelectronics Journal, 35, pp. 185-191

[8] Abdel-Rahman, E., Azenui, N.C., Korovyanko, I and Symko, O.G., 2002, "Size Considerations in Interfacing Thermoacoustic Coolers with Electronics", Proceedings of ITHERM02, Thermal and Thermomechanical Phenomena in Electronic Systems, pp. 421-424

[9] daSilva, L.W. and Kaviany, M., 2004, "Micro-Thermoelectric Cooler: Interfacial Effects on Thermal and Electrical Transport", International Journal of Heat and Mass Transfer, Vol. 47, pp. 2417-2435

[10] Grimes, R., Quin, D., Walsh, E., Davies, M. and Kunz, S., 2003, "A Theoretical and Experimental Investigation of the Scaling of Micro Fan Performance", American Society of Mechanical Engineers International Mechanical Engineering Congress and Exhibition, IMECE2003-41432, Washington DC, November

[11] Grimes, R., Walsh, E., Kunz, S., Davies, M. and Quin, D., 2003, "Scaling The Performance of Micro-Fans", American Society of Mechanical Engineers 1st International Conference on Micro and Mini Channels, NY, April

[12] Quin, D., Grimes, R., Walsh, E. and Davies, M., 2004, "The Effect of Reynolds Number on Microfan Performance", American Society of Mechanical Engineers 2nd International Conference on Micro and Mini Channels, NY, June

[13] Eason, C., Dalton, T., O'Mathuna, C., Slattery, O. and Davies, M., 2004. "Fluid Flow and Heat Transfer Performance Testing on Microchannels Using a Novel Modular Test System", 10th International Workshop on Thermal Investigations of IC's (Therminic), France, October

[14] Eason, C., Dalton, T., O'Mathuna, C., Slattery, O. and Davies, M., 2004 "Direct Comparison Between a Variety of Microchannels – Part 1: Channel Manufacture and Measurement; Part 2: Experimental Description and Flow Friction Measurement", American Society of Mechanical Engineers 2nd International Conference on Micro and Mini Channels, June, NY, June

[15] Garimella, S.V. and Singhal, V., 2003. "Single Phase Flow and Heat Transport in Microchannel Heat Sinks", American Society of Mechanical Engineers 1st International Conference on Micro and Mini Channels, NY, April

[16] Krupenkin, T.N., Ashley Taylor, J., Schneider, T.M. and Yang, S., 2004, "From Rolling Ball to Complete Wetting: The Dynamic Tuning of Liquids on Nanostructured Surfaces", Journal of the American Chemical Society, 3.8

[17] Shah, A.J., Carey, V.P., Bash, C.E. and Patel, C.D., 2004. "An Exergy-Based Control Strategy for Computer Room Air-Conditioning Units in Data Centers", American Society of Mechanical Engineers International Mechanical Engineering Congress and Exhibition, IMECE2004-61384, Anaheim CA, November

[18] Bar-Cohen, A. and Iyengar, M., 2002, "Design and Optimization of Air-Cooled Heat Sinks for Sustainable Development", IEEE Transactions on Components and Packaging Technologies, Vol. 25, Issue 4, pp. 584-591

[19] Solbrekken, G.L., Yazawa, K. and Bar-Cohen, A. 2004, "Thermal Management of Portable Electronic Equipment Using Thermoelectric Energy Conversion", Proceedings of ITHERM '04, Thermal and Thermomechanical Phenomena in Electronic Systems, Vol 1., pp. 276-283

[20] Kaivola, R. and Avikainen, T. 2001, "Noise Emission of Telecommunications Devices", Electronics Cooling, Vol. 7, No. 4, November, pp. 22-28.