Summary
The paper addresses point-of-source cooling technologies for electronic systems – heat removal techniques deployed at the location of power generation – in contrast with forced convection schemes which predominantly involve heat sinks cooled using system-level airflow. A range of contemporary 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. Finally, energy aspects of point-of-source cooling technologies are considered, with specific reference to their sink temperatures. In the context of large-scale electronic systems, greatly reduced thermal resistance paths from source to sink open opportunities for efficient cooling schemes or – potentially – the recovery of energy.

Introduction
The theme of this paper is 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 which predominantly achieve local energy removal using heat sinks, utilising system-level airflow as the medium for heat transfer. 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 [1]. 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 [2], for example. Micro-spray nozzles generate 50-100µm 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 [3], 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 [4].

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 [5] 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 contemporary microfabrication techniques. A high-frequency – 4 to 24 kHz – thermoacoustic device for electronics cooling is reported by Symko et al [6]. 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 [7].

Micro thermoelectric cells: Small scale thermoelectric cells have been realised – daSilva and Kaviany [8], for example. Thermoelectric cells are more suitable for thermal control than for cooling 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 have enabled the creation of the small scale 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.

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 1 – from Grimes et al [9] – was fabricated using a micro Electro Discharge Machining (µEDM) process, and driven by a brushless DC micro-motor.

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 2, from Grimes et al [10], 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 [11] – is presented in figure 3. 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 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 [12], and sections of the channels are illustrated in figure 4.

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 [14] 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 [15] – to microchannel geometries in order to provide control of hydrophobicity and pressure drop.

**Energy Considerations**

The thermal management of contemporary large scale electronic systems represents a substantial energy cost. Shah et al [16] indicate power densities of over 3kW/m² for data centres within 3 years, outlining a 10,000m² centre which could feature a 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 [17] 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 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 [18] 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.

**Conclusions**

A range of point-of-source thermal management technologies has been outlined, ranging 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.

Finally, energy aspects of point-of-source cooling technologies have 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.

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References


