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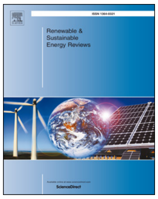

Microchannel cooling of concentrator photovoltaics: A review

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ABSTRACT

The intensifying heat flux demands of concentrator photovoltaics requires innovation beyond conventional passive air cooling. Passive cooling is cost effective, reliable and does not consume power. Flat lens arrangements should allow large passive heat sinks to cool at solar concentrations of up to 2000 suns to 4000 suns (1 sun = 1000 W/m^2). However, as solar concentrations increase so will the necessity of active cooling. The competitiveness of active cooling is enhanced by the capacity to harvest otherwise wasted thermal energy. Pairing with phase change materials presents an opportunity to stabilise the intermittent generation of solar thermal energy. Active microchannel cooling is a strong candidate for meeting the escalating heat flux demands of concentrator photovoltaics. For meeting short term-heat flux demands, established single phase microchannel cooling is most practical. Manifold microchannels yield superior performance to single layered microchannels, although they are more difficult to manufacture. For meeting long term heat flux demands, integration of boiling flows is promising. Jet impingement onto porous microstructures demonstrates effective mitigation of flow instabilities. Future studies should apply microchannel cooling directly to concentrator photovoltaics, particularly two-phase systems. They should also test microchannel cooling over larger heater areas and consider manufacturability of heat sinks. Novel directions should also be explored, such as alteration of typically rectangular and straight manifold microchannels or use of micro-valves to suppress boiling instabilities. Incipient cooling methods, including vortex shedding, ionic jet impingement, slug flow and shear driven gas flow, may also warrant further investigations.

1. Introduction

Unsustainably finite fossil fuels (oil, coal and gas) supply about 86% of the global energy consumption [1]. Associated emissions exacerbate climate change, which is laden with risks: intensification of extreme weather events, sea level rise, disruption of agricultural systems and ecosystem damage. Emissions are also immediately hazardous to health, accounting for some 3 million premature deaths in 2013 alone [2,3]. The urgency of this issue is compounded by the growing global energy demand, which is projected to increase 31% by 2035 [4].

Solar energy presents a potential solution. The historically high cost of this practically inexhaustible[1] and clean energy source has plunged 80% between 2007 and 2015. Solar is now cost competitive with coal in Germany, the U.S, Italy, Spain and Australia; and should outpace it as prices are expected to drop some 66% by 2040 [1,5]. Recent cost reductions have come from materials and manufacturing, not cell efficiencies: crystalline-Silicon cells plateauing around 25% since 2000 [6]. Concentrator photovoltaics (CPV) may drop the cost of solar power through a sharp increase in cell efficiency.

CPVs use optics (lenses/mirrors) to focus sunlight onto small multi-junction cells. Multi-junction cells are expensive and can only be feasibly used due to the cheaper concentrating optics. These multi-junction cells are highly efficient: efficiencies reaching 46% at 508 suns and expected to exceed 50% within a decade [6–8]. Most of the solar radiation striking cells is converted to heat. This can physically degrade cells and will linearly decrease cell efficiencies: crystalline-Silicon (-0.65%/K to −0.40%/K) and multi-junction (-0.15%/K to −0.05%/K) [9–11]. Multi-junction cells can operate more efficiently, than crystalline-Silicon cells, at higher temperatures (~ 80 °C) where waste heat is more practically useful. Cooling systems are required to mitigate the negative effects of heat, and to potentially harvest it for re-use in secondary applications.

Cooling demands are severe for high concentrator photovoltaics (HCPV) (300–1000 suns), where hot spots can exceed 137 W/cm^2 [8,12]. Cooling demands will increase in the future, as higher concentrations offer potential cost reductions for CPV systems [13,14]. The electronics industry faces similar challenges, average computer chip heat fluxes are expected to reach 200–450 W/cm^2 by 2026 [15]. Novel

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[1] About the same solar energy strikes the earth's surface every 100 min ($5.36\times10^{20}J$) as was consumed globally in 2015 ($5.53\times10^{20}J$) [180,181].

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Table 1
General advantages of active and passive cooling methods.

Passive	Active
Cost: Simpler manufacturing and maintenance. Lacks additional components like pumps and controls.	**Heat dissipation:** Potential to dissipate more intense heat fluxes.
Reliability: Absence of active control and requires less maintenance. Important as malfunction can damage cells and delay power generation.	**Harvest waste heat:** Fluid pumping architecture (pumps, fans, piping and control) allow for convenient utilisation of otherwise wasted thermal energy.
No parasitic losses: Does not consume power to operate, which would reduce net power generation.	**Compact:** More compact packaging, for a given heat removal rate. Relevant to shading losses.

cooling methods are required to meet these intensifying heat fluxes, such as microchannel cooling.

Microchannels are compact heat sinks loosely defined by their chancel dimensions: typically 10–200 μm but up to 1–3 mm in some cases [16–18]. Increased heat exchange areas and micro scale effects enhance heat transfer rates. However, pressure drops are also increased by the small scale. The performance of conventional single layered microchannels can be augmented by manifold structures (multiple layers), jet impingement and two-phase flows.

There are several recent reviews of photovoltaic cooling methods. However, some provide a limited assessment of microchannel cooling systems [11,19–21] or are inattentive to two-phase microchannel based systems [22–24]. Other photovoltaic cooling reviews are no longer current [25]. There are several thorough reviews of microchannel cooling methods, although these draw limited relations to the photovoltaic cooling application [16,17,26–31].

This review aims to satisfy these identified gaps; providing a review of state of the art single and two-phase microchannel cooling methods, primarily for application in CPVs. Non-microchannel cooling methods are briefly assessed, to provide context for the microchannel cooling methods. The CPV market, and prototype / utility CPV systems are also discussed. This discussion aims to enhance understanding of the microchannel cooling application (CPV) focused upon by this review. Specific fabrication methods are not addressed as this is adequately done in [32,33]. Nano technologies are not of focus, with other reviews covering the topic [23,34,35].

The paper is organized as follows: Section 2 briefly assesses non-microchannel cooling methods, including: phase change material, heat pipe, free air, liquid immersion, evaporative, forced air, thermoelectric, liquid film or spray and jet impingement cooling methods. Section 3 then thoroughly reviews single and two-phase microchannel cooling methods. Section 4 then addresses the proposed application of the microchannel cooling methods, CPVs. This is done through a concise assessment of the market, and existing utility and prototype CPV systems. Finally, Section 5 provides a concluding summary and identifies several areas of further research.

2. Non-microchannel cooling methods

There is a diverse array of photovoltaic cooling methods. These can be categorised as either active or passive. Active systems require an external power source for operation: pumps, fans or controls. Passive systems do not require an external power source for operation. They instead use natural phenomena like free convection, evaporation and wicking. Table 1 outlines the broad advantages of each type. Passive and then active PV cooling methods are now addressed.

2.1. Passive

In this paper, passive systems will encompass: phase change material, heat pipe, free air, liquid immersion and evaporation methods. Each method will be briefly described. Table 2 summarises each methods strengths and limitations. A selection of innovative and high performing cases, emerging research areas and supplementary reviews are identified.

2.1.1. Phase change material

Phase change materials function like a rechargeable thermal battery. They are substances which can store and release large amounts of thermal energy, almost isothermally, due to large latent heat capacities.[2] Phase change materials can cool photovoltaic cells by absorbing their excess heat during the day (melting) and releasing it to the environment during evenings (solidifying). Alternatively, this heat can be harvested for other purposes such as space or water heating.

Phase change materials are suited to PV thermal and building-integrated PV thermal systems. This due to their capacity to store, then release, large amounts of thermal energy for extended periods. Compared to similar water photovoltaic-thermal systems, phase change materials can store about 33% more heat and extend its availability by 75–100% [36].

The performance of phase change materials is largely dependent on static material properties and prevailing environmental conditions. This inflexible performance makes material reliable solidification a challenge. Areas with low inter-seasonal variation and high solar insolation are preferable [37]. Phase change materials have poor thermal conductivities which inhibits cooling rates and temperature uniformity. Use of conductive fins or material housings can effectively counteract this, although this increases systems costs. Unreliable performance and high costs currently prevent the commercial viability of phase change materials.

Emerging research areas include microencapsulation [38,39], salt hydrates, compressed expanded natural graphite [40–42] and segmentation of different material types [43]. Building integrated photovoltaic-thermal also presents an opportune application. Supplementary information can be found in several recent reviews [36,37,44–46].

2.1.2. Heat pipe

Heat pipes are flat or round pipes which employ an internal evaporation-condensation cycle to attain very low thermal resistances across their length. Heat pipes can be used to transport heat away from CPV's small cell surfaces, where space is limited. Acting as a heat spreader. Heat pipes have narrow, pre-designed, operating conditions. Consequently, heat pipes can suffer from instability issues: overheating, flooding during start up or oscillatory or backwards thermal flows. Heat pipes have demonstrated suitability at higher concentrations, around 500–700 suns [47,48]; and in photovoltaic-thermal systems [49]. Reducing the cost of heat pipes presents direction for future research. Several reviews provide further information [19,20,50,51].

2.1.3. Free air

Free air systems use natural convection to dissipate heat. Heat exchange areas are extended with dedicated heat sinks or through the adjoining support structure. This cooling method is adopted by almost all utility scale CPV systems, largely via the structure depicted in Fig. 5. These systems are prevalent due to their simplicity, low cost and reliability. Limited thermal resistances will eventually restrict use at higher solar concentrations. Immersion may allow passive cooling at

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[2] Phase change materials can store about 5–14× more heat than sensible storage materials like water, masonry and rock [182].