nature research
https://doi.org/10.1038/s41586-020-2666-1

Supplementary information

Co-designing electronics with microfluidics for more sustainable cooling

In the format provided by the
authors and unedited

Benchmarking of direct cooling approaches in the literature using water as a working fluid

Supplementary data to: van Erp et al, 2020, *Co-designing electronics with microfluidics for more sustainable cooling*

Reference	Authors	Year	Approach	Geometry	Application	Work	A	N	w	z	Flow rate	Pressure drop	Pumping power	R_t	q_{max} 60K	Q_{max} 60K	COP 60K	Note
							cm2		um	um	ml/s	mbar	W	K/W	W/cm2	W	[-]	
This work - 10x manifold	van Erp	2020	Direct	mMMC	Power electronics	Experimental	0.081	1	20	125	0.45	193	0.009	0.601	1233	100	11525	10x manifold
							0.081	2	20	125	0.568	249	0.014	0.540	1373	111	7860	
							0.081	3	20	125	0.769	345	0.027	0.496	1492	121	4552	
							0.081	4	20	125	0.893	405	0.036	0.457	1621	131	3632	
							0.081	5	20	125	1	456	0.046	0.438	1690	137	3002	
This work - 4x manifold	van Erp	2020	Direct	mMMC	Power electronics	Experimental	0.081	1	20	125	0.158	149	0.002	1.807	410	33	14113	4x manifold
							0.081	2	20	125	0.263	407	0.011	1.292	573	46	4336	
							0.081	3	20	125	0.358	677	0.024	1.008	735	60	2456	
							0.081	4	20	125	0.447	950	0.042	0.876	845	68	1614	
							0.081	5	20	125	0.521	1249	0.065	0.804	921	75	1146	
							0.081	6	20	125	0.580	1572	0.091	0.753	984	80	874	
							0.081	7	20	125	0.625	1932	0.121	0.706	1049	85	704	
							0.081	8	20	125	0.713	2197	0.157	0.676	1096	89	567	
							0.081	9	20	125	0.770	2515	0.194	0.645	1149	93	480	
High-performance heat sinking for VLSI	Tuckerman & Pease	1981	Direct	PSM	Logic (VLSI)	Experimental	1	1	56	320	4.7	1034	0.486	0.110	545	545	1122	Data derived from Table 1
							1	2	55	287	6.5	1172	0.762	0.113	531	531	697	
							1	3	50	302	8.6	2137	1.838	0.090	667	667	363	
Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies	Ndao et al.	2009	Direct	PSM	General	Optimization	1	1	-	-	-	300	0.100	0.125	480	480	4800	No dimensions are given since they were optimized per heat flux
							1	2	-	-	-	500	0.200	0.110	545	545	2727	
							1	3	-	-	-	700	0.400	0.093	645	645	1613	
							1	4	-	-	-	900	0.600	0.084	714	714	1190	
							1	5	-	-		900	1.000	0.080	750	750	750	
Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies	Ndao et al.	2009	Direct	In-line pin fin	General	Optimization	1	1	-	-	-	300	0.200	0.100	600	600	3000	No dimensions are given since they were optimized per heat flux
							1	2	-	-	-	500	0.500	0.078	769	769	1538	
							1	3	-	-	-	700	1.000	0.069	870	870	870	
							1	4	-	-	-	900	2.500	0.060	1000	1000	400	
Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies	Ndao et al.	2009	Direct	In-line pin fin	General	Optimization	1	1	-	-	-	300	0.200	0.100	600	600	3000	No dimensions are given since they were optimized per heat flux
							1	2	-	-	-	500	0.500	0.070	857	857	1714	
							1	3	-	-	-	700	0.750	0.068	889	889	1185	
							1	4	-	-	-	900	2.500	0.057	1053	1053	421	
Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies	Ndao et al.	2009	Direct	Strip fin	General	Optimization	1	1	-	-	-	300	0.250	0.069	870	870	3478	No dimensions are given since they were optimized per heat flux
							1	2	-	-	-	500	0.900	0.050	1200	1200	1333	
							1	3	-	-	-	700	1.400	0.045	1333	1333	952	
							1	4	-	-	-	900	3.000	0.040	1500	1500	500	
Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies	Ndao et al.	2009	Direct	Single Jet	General	Optimization	1	1	-	-	-	300	0.280	0.230	261	261	932	No dimensions are given since they were optimized per heat flux
							1	2	-	-	-	500	0.400	0.205	293	293	732	
							1	3	-	-	-	700	0.580	0.186	323	323	557	
							1	4	-	-	-	900	2.000	0.160	374	374	187	
							1	5	-	-	-	900	4.000	0.160	375	375	94	
Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies	Ndao et al.	2009	Direct	Mulitple Jet	General	Optimization	1	1	-	-	-	300	0.300	0.120	500	500	1667	No dimensions are given since they were optimized per heat flux
							1	2	-	-	-	500	1.200	0.075	800	800	667	
							1	3	-	-	-	700	2.550	0.064	938	938	368	
							1	4	-	-	-	900	4.350	0.062	976	976	224	
							1	5	-	-	-	900	6.230	0.058	1034	1034	166	

A single phase hybrid micro heat sink using impinging micro-jet arrays and microchannels	Robinson et al.	2018	Indirect	Finjet (MMC/Jet combination)	Ext. cooler	Numerical	0.12	1	35	700	8.3	1000	0.83	0.12	2220	266	321	Indirect cooling: cooler should be mounted to a chip, interfaces and thermal resistance over the die are not included in this thermal resistance
Manifold microchannel cooler for direct backside liquid cooling of SiC power devices	Everhart et al.	2007	Bare die	MMC bare die cooling	Power diode	Experiment	0.16	1	200	800	1	345	0.035	0.525	714	114	3313	MMC structure, but channels were not integrated in the active device, so could be classified as bare die cooling. Derived from Fig. 7 and Table 2
							0.16	2	200	800	1.6	689	0.110	0.469	800	128	1161	
							0.16	3	200	800	2	1034	0.207	0.419	896	143	693	
							0.16	4	200	800	2.4	1379	0.331	0.419	896	143	433	
Experimental Investigation of an Ultrathin Manifold Microchannel Heat Sink for Liquid-Cooled Chips	Escher et al.	2010	Direct	MMC	Logic	Experiment	4	1	108	298	18	110	0.198	0.039	387	1548	7820	Derived from Fig. 7-8 (Case 1-6)and the abstract (case 7)
							4	2	108	298	18	140	0.252	0.039	387	1548	6144	
							4	3	57	264	18	130	0.234	0.029	513	2051	8766	
							4	4	57	264	18	150	0.27	0.030	500	2000	7407	
							4	5	26	226	18	210	0.378	0.025	600	2400	6349	
							4	6	26	226	18	155	0.279	0.026	571	2286	8193	
							4	7	26	226	21.7	220	0.477	0.023	667	2667	5594	
A Practical Implementation of Silicon Microchannel Coolers for High Power Chips	Colgan et al.	2005	Direct	Offset strip fins	Logic	Experiment	3	1	75	180	38.33	320	1.227	0.035	571	1714	1398	Derived from Fig. 5. Both direct and indirect approach was demonstrated, but indirect results are not listed in this table. Indirect cooling yielded roughly double the thermal resistance with thinned down die and solder-bond
							3	2	75	180	25.00	172	0.430	0.040	500	1500	3488	
							3	3	75	180	21.67	138	0.299	0.044	455	1364	4561	
							3	4	75	180	31.67	255	0.808	0.037	536	1607	1990	
Embedded cooling of high heatflux electronics utilizing distributed microfluidic impingement jets	Ditri et al.	2015	Bare die	Jet impiging	Bare die cooling	Numerical and experimental	0.13	1	60	-	2	7650	1.53	0.384615385	1200	156	102	Datapoints taken from benchmarking in Robinson 2018. Thermal resistances are average and not max values.
Package-level Si-Based Micro-jet Impingement Cooling Solution With Multiple Drainage Micro-Trenches	Han et al.	2014	Indirect	Hybrid Jet/microchannel, similar to MMC	RF power amplifier	Simulation	0.64	1	250	250	-	-	0.2	0.1116	840	538	2688	Data derived from the conclusions
Extending the heat flux limit with enhanced microchannels in direct single phase cooling of computer chips	Kandlikar & Upadye	2005	Direct	Strip fin	General	Experimental	1	1	200	200	0.35	40	0.001	0.600	100	100	71429	Derived from combining the data in Fig. 8 and Fig. 9. The split-flow results could not be benchmarked due to missing flow rate data
							1	2	200	200	0.52	40	0.002	0.600	100	100	48077	
							1	3			0.75	150	0.011	0.343	175	175	15556	
							1	4			1.75	150	0.026	0.343	175	175	6667	
							1	5			1.60	410	0.066	0.240	250	250	3811	
							1	6			3.90	475	0.185	0.240	250	250	1350	
Microjet Cooler with Distributed Returns	Natarajan & Benzema	2007	Bare Die	Multi-jet	Logic	Simulation	0.031	1	126	300	0.399	170	0.007	7.183	272	8	1232	Not silicon but ceramic, bare die cooling. Authors did fabricate the cooler, but extracted data for benchmarking was based on CFD results. Data derived from Table 3. Flow rate was derived from multiplying Vj with the surface area of 16 jet openings
							0.031	2	126	300	0.598	330	0.020	6.300	310	10	482	
							0.031	3	126	165	0.399	190	0.008	7.550	259	8	1049	
High Efficiency direct liquid jet impingement cooling of high power devices using a 3D-shaped polymer cooler	Wei et al.	2018	Bare Die	Multi-jet	Bare die cooling	Experiment	0.64	1	450	300	4.667	81	0.038	0.420	223	143	3759	Data derived from Fig. 13 and Fig. 16. Pressure drop derived from pumping power
							0.64	2	450	300	10	400	0.400	0.250	375	240	600	
Interlayer cooling potential in vertically integrated packages	Brunschwiler	2008	Direct	Pin-Fin Staggered	3D integration	Experiment	1	1	133	200	-	-	0.015	-	190	190	12667	Derived from q-P plot PFS-p200-h200
							1	2	133	200	-	-	0.050	-	290	290	5800	
							1	3	133	200	-	-	0.250	-	450	450	1800	
Interlayer cooling potential in vertically integrated packages	Brunschwiler	2008	Direct	Distorted Pin-Fin staggered	3D integration	Experiment	1	1	150	200	-	-	0.030	-	275	275	9167	Derived from q-P plot PFS-dc-p200-h200
							1	2	150	200	-	-	0.055	-	390	390	7091	
							1	3	150	200	-	-	0.120	-	550	550	4583	
							1	4	150	200	-	-	0.400	-	700	700	1750	
Interlayer cooling potential in vertically integrated packages	Brunschwiler	2008	Direct	In-line pin fin	3D integration	Experiment	1	1	133	200	-	-	0.011	-	190	190	17273	Derived from q-P plot PFI-p200-h200-hp
							1	2	133	200	-	-	0.055	-	280	280	5091	
							1	3	133	200	-	-	0.130	-	400	400	3077	
							1	4	133	200	-	-	0.380	-	520	520	1368	
Three-dimensional							1	1	25	250	-	-	0.1	0.052	1154	1154	11538	

Three-dimensional numerical optimization of a manifold microchannel heat sink	Ryu	2003	Direct	MMC	General	Optimization	1	2	20	200	-	-	0.5	0.040	1500	1500	3000	Optimized values derived from q-Rt plot
							1	3	15	150	-	-	2.5	0.032	1875	1875	750	
							1	4	12	120	-	-	10	0.024	2500	2500	250	
Next Generation Microchannel Heat Exchangers	Ohadi	2013	Direct	MMC	General	Numerical	4.8E-04	1	72	480	-	1.3	1.06E-07	417	300	0.14	1363636	Only numerical data was taken of a single unit cell, because it used water as a working fluid. Datapoint 1 should be interpreted with caution as the simulation temperature surpassed the boiling temperature of water
							4.8E-04	2	72	480	-	17	1.09E-05	138	909	0.44	39995	
							4.8E-04	3	72	480	-	140	3.79E-04	83	1500	0.72	1901	
Embedded cooling with 3D manifold for vehicle power electronics application: Single-phase thermal-fluid performance	Jung	2019	Direct	MMC	Vehicle power electronics	Experimental	0.25	1	75	150	0.55	2.9	1.60E-04	1.300	185	46.2	289366	-
							0.25	2	75	150	1.15	11.7	1.35E-03	0.810	296	74.1	55053	
							0.25	3	75	150	1.717	23.6	4.05E-03	0.650	369	92.3	22785	