In-slot Cooling of Electrical Machines Using Traditional Techniques and Additive Manufacturing

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Keywords

«Additive manufacturing», «Efficiency», «Electric machines», «In-slot cooling»

Abstract

This paper covers in-slot cooling methods used for the effective cooling of electric machines. Both traditional and additively manufactured cooling solutions are discussed throughout the paper. A new additively manufactured heat exchanger is also presented in the paper. It is shown that the proposed solution can boost current density to 83 A_{rms}/mm^2 using PCB as stator winding.

Introduction

Cooling of electric machines is becoming more important as researchers push the boundaries of power density for electric machines. The winding conductors are one of the critical parts that need superior cooling performance due to high conduction losses. In-slot cooling methods are getting attention for effective cooling of the winding conductors and the back iron. The cooling channels are placed inside the slots. These methods achieve superior current densities in the windings by placing the cooling channels very close to the conductors.

In the first part, this paper reviews in-slot cooling methods manufactured by traditional methods and additive manufacturing technology, which enables the manufacturing of complex geometries. Key metrics such as winding temperature, fill factor, and current density are collected from the reviewed literature. In the second part, this paper proposes in-slot cooling solutions for electric machines using a 3D printed heat exchanger with PCB winding and a flat wire winding. The performance of the presented solutions is also compared with the reviewed solutions in the literature.

Traditional in-slot cooling methods

Traditional in-slot cooling methods are categorized into three groups: liquid cooling with heat exchangers, in-slot cooling with heat pipes and heat guides, and forced air in-slot cooling. These cooling methods can be manufactured using conventional methods instead of additive manufacturing technology.

Liquid cooling with heat exchangers

Traditionally manufactured solutions utilizing heat exchangers (HX) include a variety of designs. One such design is proposed in [1], which utilizes the gap between two adjacent windings of a double-layer

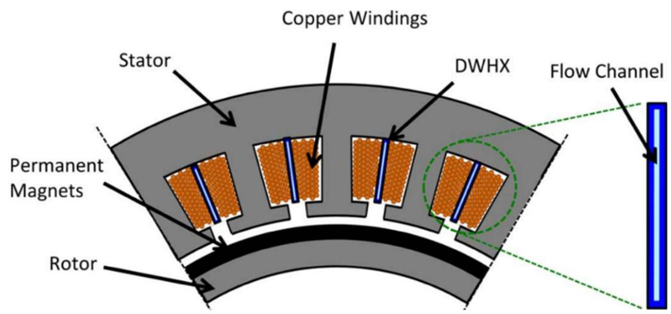
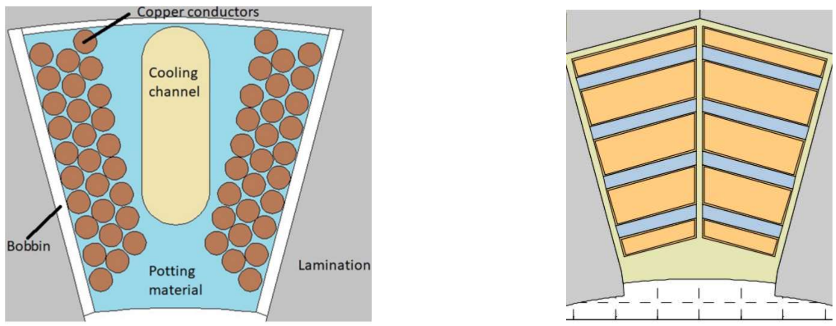


Fig. 1. Copper heat exchanger between adjacent windings [1].



(a) (b)

Fig. 2. a. Cooling channel formed by thermally conductive epoxy [2] b. Cooling channels interleaved between flat conductors [3].

concentrated winding. A copper HX is placed in this gap with coolant flowing inside it. This design is shown in Fig. 1. The authors report a continuous current density of 25 A_{rms}/mm^2 and a transient current density of up to 40 A_{rms}/mm^2 at a hotspot temperature of 155 °C. The flow rate is set to 5300 cc/min, and the maximum pressure drop through the system is measured as 5.14 kPa. The experimental work is carried out by removing the rotor in the machine (nonrotating machine). Therefore, the core losses are not included in the results.

Another in-slot cooling design is proposed in [2], where a cooling channel between adjacent windings is formed using a thermally conductive epoxy during global winding encapsulation, as shown in Fig. 2a. The current densities are reported to be 25 A_{rms}/mm^2 continuous and 35 A_{rms}/mm^2 peak at a hotspot temperature of 180°C and a fill factor of 0.32. Oil is used as a coolant with an inlet temperature of 60 °C and a flow rate of 6 L/min. A pressure drop of 42 kPa is reported under the operating conditions. A more aggressive approach is presented in [3], where multiple layers of flat conductors are interleaved with cooling channels, as shown in Fig. 2b. The maximum continuous current density is reported to be 50 A_{rms}/mm^2 with hotspot temperatures below 120 °C and a fill factor of 0.47. Oil is used as a coolant at a 2 L/min flow rate and 40 °C of inlet temperature. However, no manufacturing method is proposed for this highly complex design.

In-slot cooling with heat pipes and heat guides

Heat pipes are another effective in-slot cooling method with very high thermal conductivity. Heat pipes are sealed pipes made from a thermally conductive metal, mainly copper or aluminum, containing water vapor. A pressure gradient inside the pipe causes circulation of the liquid and gaseous phases, which causes a convection heat transfer inside a sealed tube. On the other hand, a heat guide is just a solid made from a thermally conductive material, which causes a conduction heat transfer.

One application of heat pipes and heat guides for in-slot cooling is shown in Fig. 3. In this study, heat is removed by employing heat pipes inside the slot bottom paired with a heat guide to cover the empty area in the middle of the slot. Two designs are evaluated: one with a cooling jacket and heat pipes and the other with just the heat pipes. The design paired with a cooling jacket achieved 24 A_{rms}/mm^2, whereas

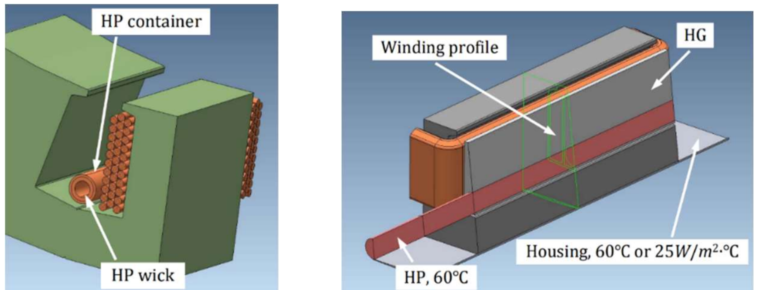


Fig. 3: In-slot heat pipe with heat guide [5]

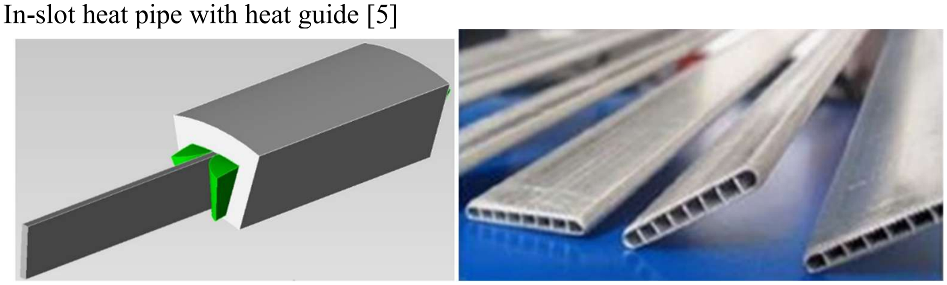


Fig. 4. a. Flat heat pipe for in-slot cooling b. Internal structure of flat heat pipe [6]

the design without the cooling jacket achieved 21 A_{rms}/mm^2. In both these cases, the winding hotspot temperature was kept at 180 °C, and a fill factor of 0.38 was achieved [4], [5]. Another heat pipe-based design is presented in [6], which uses a flat heat pipe covering the gap between adjacent windings in a double-layer concentrated wound stator, as shown in Fig. 4. The maximum current density achieved is 16.5 A_{rms}/mm^2 with a fill factor of 0.4 and a hotspot temperature of 95 °C.

A tubular linear motor is presented in [7], as shown in Fig. 5, with a double layer concentrated wound stator using a heat guide between the adjacent winding gap paired with a stator cooling jacket. This heat guide is made from aluminum, which reduces the thermal resistance between the winding hotspot and the actively cooled stator back iron. The reported current density is 35 A_{rms}/mm^2 at 180 °C hotspot temperature.

Forced air in-slot cooling

Air cooling is generally cheaper and more robust compared to any form of liquid cooling. Forcing air through slots is achieved using cast coils in a design presented in [8]. Aluminum cast coils are used with axial airflow to remove the heat combined with a stator cooling jacket. The casting process allows for slot fill factors of up to 0.9 and continuous current densities of up to 24 A_{rms}/mm^2 while keeping the hotspot temperature below 180 °C. The aluminum cast coil is shown in Fig. 6. Another forced air convection cooled aluminum winding is shown in Fig. 7 to be employed in a stator as a wave winding [9]. The peak current density is 30 A_{pk}/mm^2 with a maximum hotspot temperature of 180 °C. In this case, the windings are laminated with spaces between each layer to allow airflow, which provides convection for cooling.

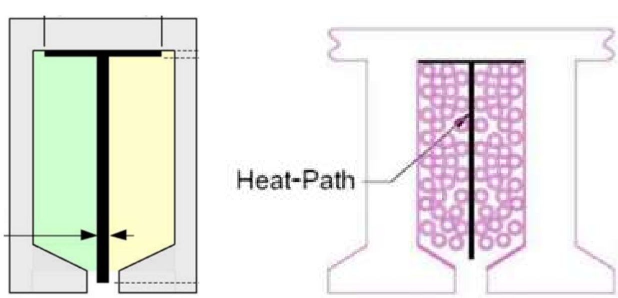


Fig. 5. Aluminum heat path between winding and back iron [7]

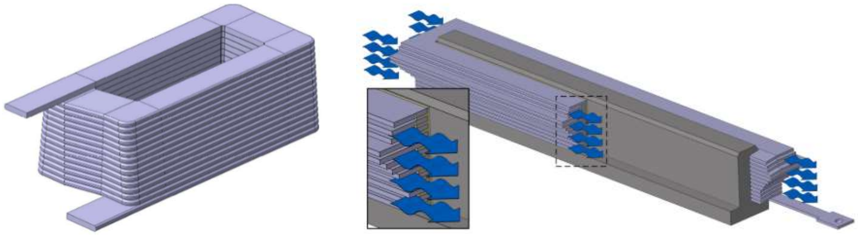


Fig. 6. Aluminum cast coils with axial airflow [8]

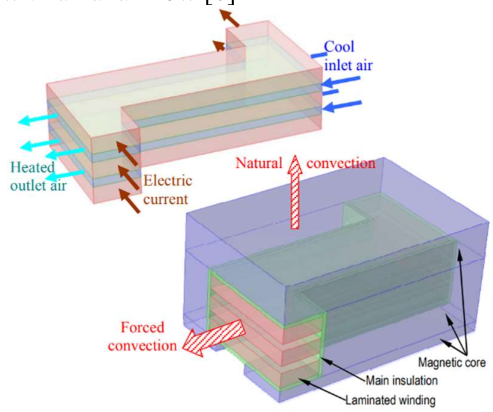


Fig. 7. Forced convection for AM winding [9]

Additively manufactured in-slot cooling solutions

Additively manufactured heat exchangers

AM enables design freedom for manufacturing complex geometries required for HXs. A liquid-cooled version of in-slot HX is presented in [10] for use with rectangular wire. The cooling channel is formed by 3D printing a tube insert with a water-soluble plastic (polyvinyl alcohol (PVA) in this case). This tube occupies the gap between adjacent double-layer concentrated windings in a slot, which is then encapsulated. After curing, the water-soluble insert is dissolved, and a cooling channel is formed, as shown in Fig. 8. A fill factor of 0.545 is achieved with rectangular wire. The authors report a current density of 20 A_{rms}/mm^2 with a hotspot temperature of 85 °C. The authors measured the performance of the heat exchanger on a 70 kW machine with 1.2 kW of copper losses. A 50/50 water/glycol mixture is used as a coolant with an inlet temperature of 50 °C.

Another example of in-slot cooling is presented in [11], where a 3D-printed direct winding HX (3DWHX) is made from aluminum-flake polycarbonate. The HX is inserted in the gap between the adjacent windings of a double-layer concentrated wound machine, as shown in Fig. 9. The HX can be encapsulated with the windings to provide good thermal contact. The authors report a current density of 20 A_{rms}/mm^2 tested in a motorette where the windings were not encapsulated. Theoretically, with a

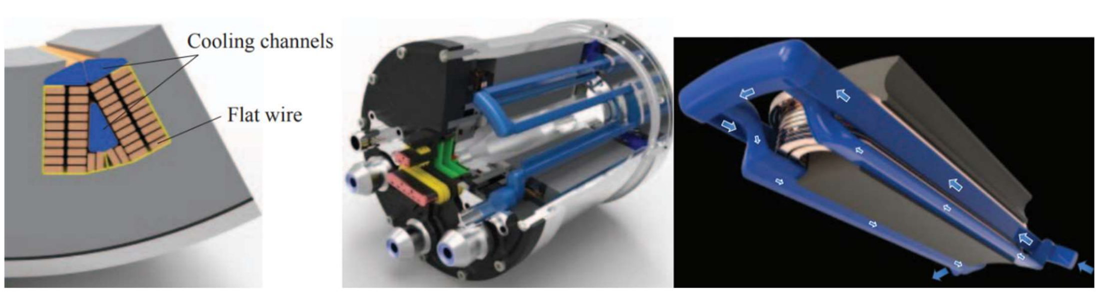


Fig. 8. In-slot heat exchanger using PVA molds [10]

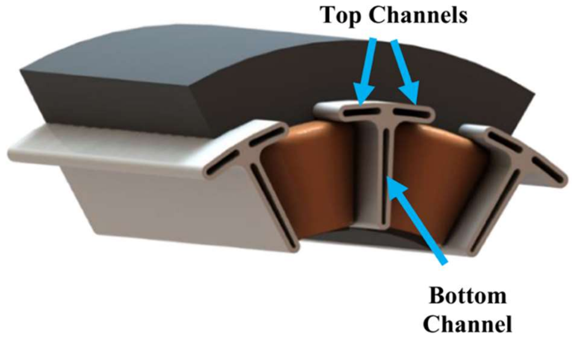


Fig. 9. 3D-printed direct winding HX for a double layer concentrated wound machine [12]

hotspot temperature of 195 °C, the current density could be increased to 33 A_{rms}/mm^2. Another similar HX is made from 3D-printed alumina, which allows a current density of 35 A_{rms}/mm^2 with a hotspot temperature of 200 °C [12]. Water is used as a coolant with a flow rate of 0.95 L/min. In both cases, the fill factor was assumed to be around 0.5 in the area occupied by windings, excluding the area occupied by the HX, and around 0.28 for the total slot area.

Additively manufactured heat guide

Like the traditionally manufactured heat guides, AM heat guides can also provide effective in-slot cooling while conforming to the complex shapes for better thermal contact and lower contact resistance. One such AM-based heat guide is presented in [13]. This heat guide, like others, occupies the gap between neighboring double-layer concentrated windings and conducts the heat produced by the windings to the stator housing, which is actively cooled. The heat guide is 3D-printed with AlSi10Mg, which can manage up to 40% additional power loss for the same temperature rise with a 180 °C hotspot temperature. This heat guide is shown in Fig. 10.

Additively manufactured hollow windings with integrated cooling

In addition to cooling channels and heat guides, 3D-printing has also been utilized to design liquid-cooled coils for electric machines. In [14], a 3D-printed AlSi10Mg coil is designed and compared to a similarly sized cast copper coil. The 3D-printed coil is shown in Fig. 11, submerged in coolant instead of a separate heat exchanger, achieving extremely high current densities. With hotspot temperature limited to 180 °C, the cast copper coil has a tested DC current density of 100 A_{rms}/mm^2, whereas the 3D-printed coil has a possible theoretical current density of 70 A_{rms}/mm^2. The fill factor is not reported for the 3D-printed coil used in this study.

A more integrated system is proposed in [15] with hollow AM coils integrated with heat pipes. The coils are printed with AlSi10Mg and are hollow from the inside to allow for the insertion of copper heat pipes, which can conduct heat at a very high rate. The system is shown in Fig. 12, where the authors report a current density of 13.9 A_{rms}/mm^2.

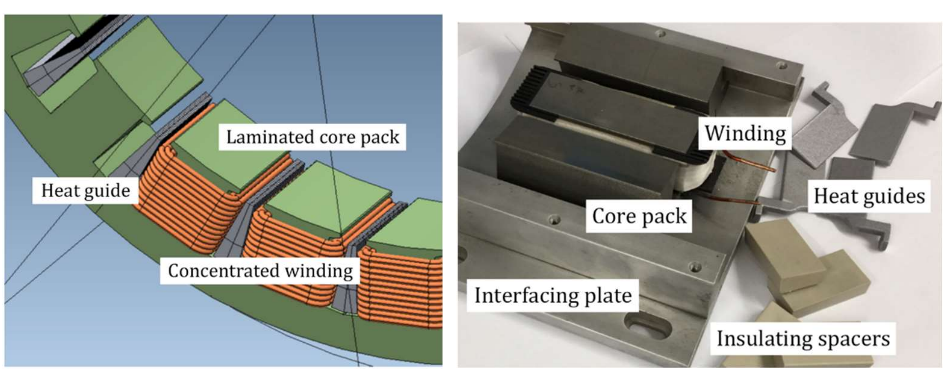


Fig. 10. AM heat guide a. 3D CAD assembly b. Prototype motorette [13]

(a) (b) (c)

Fig. 11. 3D printed coil for submerged cooling a. Front view b. Top view c. Insulated coil in a coolant tank [14]

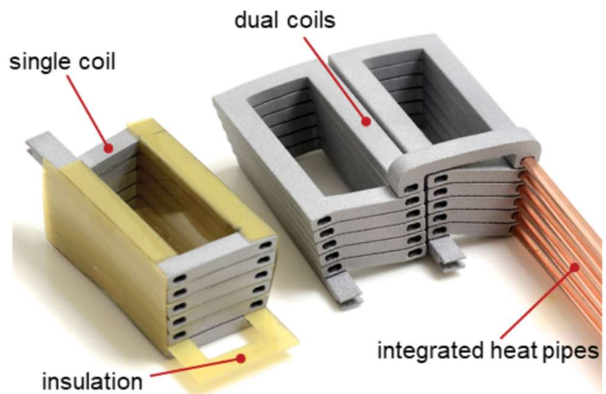


Fig. 12. AlSi10Mg coils integrated with heat pipes [15]

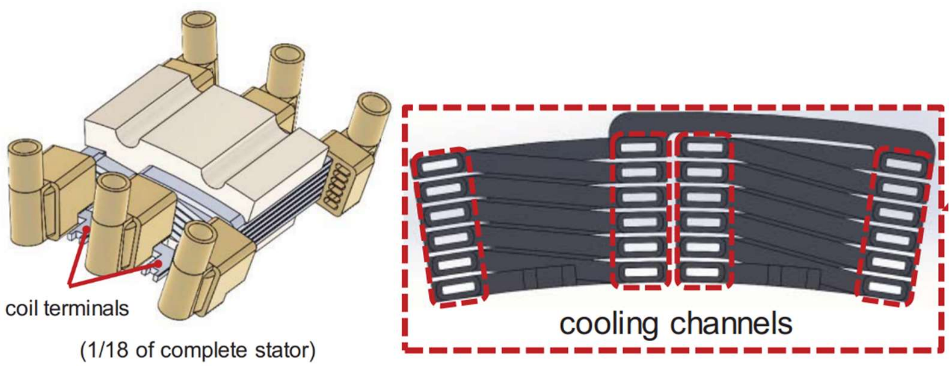


Fig. 13: Hollow AM conductors with cooling channels [16]

An even more integrated design along the same lines eliminates the heat pipes [16]. In this case, the coolant flows inside the hollow conductors, printed with AlSi10Mg, as shown in Fig. 13. The conductors are used for an aerospace SPM machine with a current density of 20 A_{rms}/mm^2 and a machine-specific power of 20.17 kW/kg.

Proposed 3D printed heat exchanger with PCB winding

The first proposed heat exchanger and winding combination utilizes PCBs and 3D printed heat exchangers to achieve a high current density. PCBs have flat conductors with large surface areas, which are extremely efficient in heat dissipation. The advantages of using a PCB-based winding are the possibility of a modular system, streamlining mass production, and reduced cost. However, the disadvantage is that the copper thickness is small compared to the substrate thickness. The PCB substrate does not play any advantageous role in electromagnetic or thermal performance. The proposed PCB winding with HX is shown in Fig. 14a. This topology is utilized for a 12-slot, 10-pole SPM machine with a double-layer concentrated winding. The slot winding area is square to make the insertion of fully assembled winding modules from the airgap side. The finned HX can be slid in from the axial side once the PCB winding is in place. Thermally conductive epoxy is used between the copper layer and the HX fin to form a good thermal contact for maximum heat transfer, as shown in green in Fig. 14b. The presented version, as shown in Fig. 14, shows 16 turns per winding.

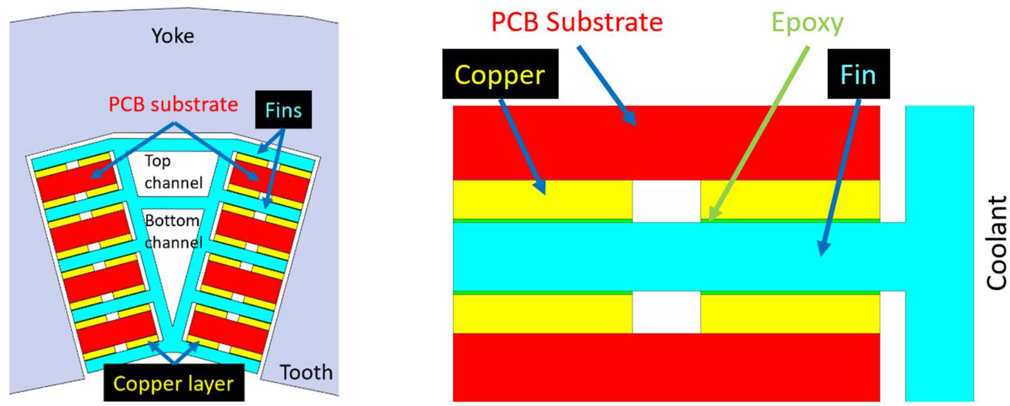


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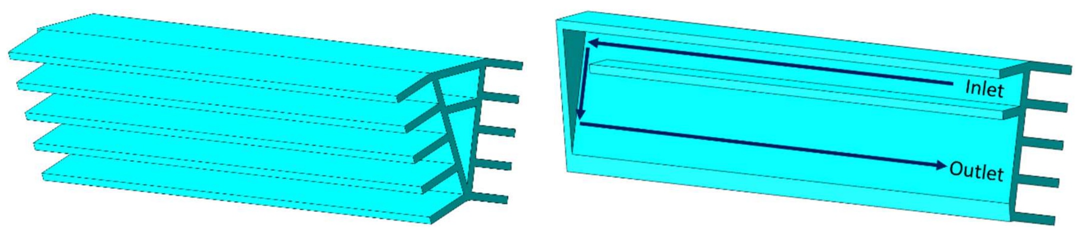
Fig. 14. a. Proposed in-slot heat exchanger b. Zoomed in PCB winding with heat exchanger



a b

Fig. 15. a. Proposed finned HX b. Cross-section and coolant path

The HX is a triangular duct with fins extending from the walls. The duct has a water-ethylene glycol mixture flowing inside it with a return feature, as shown in Fig. 15. The return feature makes it possible to have the coolant inlet and outlet on the same side of the machine. The whole assembly (duct and fins) is designed to be 3D-printed from a thermally conductive material. Currently, two materials are under consideration. The first one is a thermoplastic polyurethane (TPU) filament with thermal conductivity of 6 W/m-K and a maximum operating temperature of 110°C, while the other is a thermally conductive nylon filament with thermal conductivity of 4 W/m-K and maximum operating temperature of 200°C. The PCB substrate has a maximum temperature limit of 170°C. The slot component parameters are given in Table I [17].

For TPU, the conductor's maximum steady-state current density is 92.9 A_{rms}/mm^2, while the slot current density is 19.8 A_{rms}/mm^2 at a hotspot temperature of 110°C. For nylon, the conductor current density is 138.5 A_{rms}/mm^2, while the slot current density is 29.5 A_{rms}/mm^2 at a hotspot temperature of 170°C, limited by the PCB substrate. The slot current densities are calculated by excluding the area occupied by the cooling channel. The higher current density for the lower thermal conductivity material is due to the higher operating temperature.

Table I. Slot and winding parameter values for PCB winding

Parameter	Value
Copper thickness	13 Oz. (0.455 mm)
PCB substrate thickness	1.6 mm
Thermal epoxy thickness	0.4 mm
Fin thickness	0.8 mm
Coolant temperature	70 °C
Heat transfer coefficient	14000 W/m^2-K
Pressure drop (one channel)	150 Pa

Proposed 3D printed heat exchanger with flat wire winding

This version of the proposed heat exchanger utilizes a flat copper wire, and rectangular 3D printed heat exchangers to achieve a high current density. The advantages of this type of winding are that there is no limit on copper thickness, no substrate, and a higher fill factor with a higher number of turns can be achieved. The proposed winding with HX is shown in Fig. 16a. This topology is also utilized for a 12-slot, 10-pole SPM machine with a single-layer concentrated winding. The HX and winding are assembled outside the stator and form a module inserted in the slots from the air gap side, forcing the slots to be square. Thermally conductive epoxy is used between the copper layer and the HX, just like in the first case, to form a good thermal contact for maximum heat transfer, as shown in green in Fig. 16b. The current version, as shown in Fig. 16, shows 32 turns per winding module (in two layers).

The HX, in this case, is a rectangular duct with a water-ethylene glycol mixture flowing inside it. The return feature is formed by connecting ducts from two adjacent slots, as shown in Fig. 17, to keep the inlet and outlet on the same side of the machine. The duct is designed to be 3D-printed from the same two thermally conductive materials proposed in the first case. The slot component parameters are given in Table II.

For TPU, the conductor's maximum steady-state current density is 50.5 A_{rms}/mm^2, while the slot current density is 25.6 A_{rms}/mm^2 at a hotspot temperature of 110°C. For nylon, the conductor current density is 75.9 A_{rms}/mm^2, while the slot current density is 38.5 A_{rms}/mm^2 at a hotspot temperature of 190°C. The higher slot current densities, despite the lower conductor current densities, are attributed to higher slot fill factors achieved by using flat wire instead of PCB.

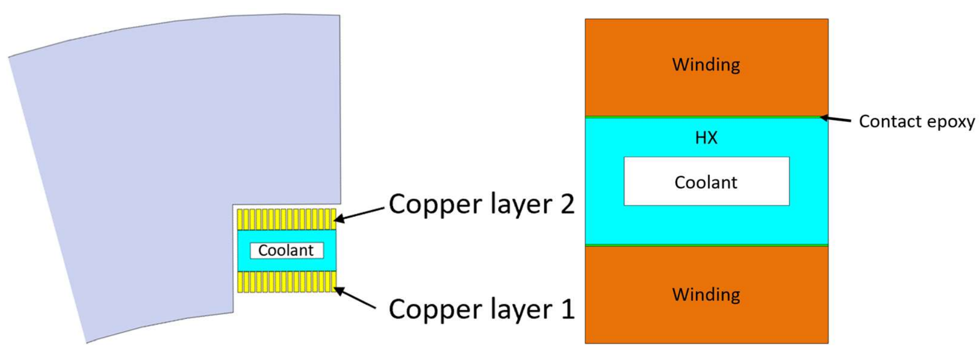


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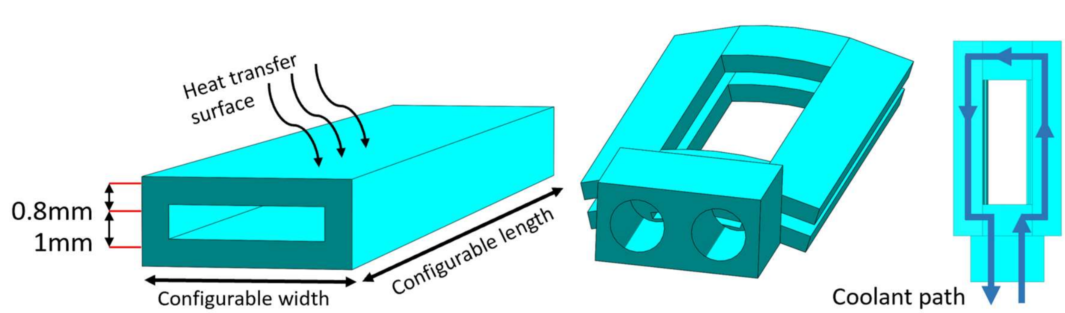
Fig. 16. a. Proposed in-slot heat exchanger with flat wire winding b. Zoomed in winding with heat exchanger



a b

Fig. 17. a. Proposed rectangular HX, b. Coolant path

Table II. Slot and winding parameter values for flat wire winding

Parameter	Value
Copper thickness	1.4 mm
Thermal epoxy thickness	0.2 mm
HX wall thickness	0.8 mm
HX coolant channel height	1 mm
Coolant temperature	70 °C
Heat transfer coefficient	6000 W/m^2-K

Discussion

For discussion purposes, a number of papers are selected for both traditional and AM-based techniques in Table III to create a contrast between the solutions. The critical parameters such as current density, fill factor, or hotspot temperature can give an idea about the performance comparison of the selected in-slot cooling methods. It should be noted that the fill factor definition for different publications may be different.

Compared with liquid-cooled heat exchangers, the heat pipes can provide a more cost-effective solution because of less complexity and hardware requirement. However, they may not be ideal for high-power applications due to their limited cooling capacity. On the other hand, more aggressive cooling can be achieved with liquid cooling using heat exchangers. The flow rate is one of the parameters for heat exchangers that can be adjusted according to the cooling requirements of the machine. Compared to previous solutions, forced air cooling through slots provides less complexity with comparable current density ratings. However, reliability issues arise due to airflow leakage, especially at high-speed operations.

The additively manufactured solutions enable more complex cooling system designs to boost the cooling performance. Using AM technology, both metal and non-metal cooling solutions can be manufactured. The advantage of non-metal solutions, such as the epoxy design in [10], is that the induced eddy current losses on the material due to slot flux leakages can be eliminated. Additive manufacturing technology developments also allow printing materials with various properties like thermal conductivity. From the cost perspective, additive manufacturing can be more expensive compared to traditional techniques. However, with the developments in this emerging field, manufacturing costs are also decreasing.

Table III: Comparison of the in-slot cooling solutions by traditional and AM methods

	Traditional technique				Additive manufacturing				
Reference	[1]	[2]	[5]	[9]	This work	[10]	[12]	[13]	[16]
Cooling method	Heat exc.	Heat exc.	Heat pipe	Forced air	Heat exc.	Heat exc.	Heat exc.	Heat guide	Hollow cond.
Material	Cu	Epoxy	Cu	-	Nylon	Epoxy	Alum.	AlSi10 Mg	AlSi10 Mg
Coolant	Water	Oil	Liquid gas	Air	Water glycol	Water glycol	Water	-	Liquid
Current density [A_{rms}/mm^2]	25	25	24	21	75.9	20	35	-	20
Fill factor	0.40	0.32	0.38	-	0.51	0.55	0.28	-	-
Hotspot temp. [°C]	155	180	180	180	190	85	200	180	110
Inlet temp. [°C]	30	60	60	25	70	50	30	60	85

Conclusion

In-slot cooling methods are shown to be effective in cooling the stator winding conductors. Both traditional and additively manufacturing methods provide superior cooling performance. It is shown that the slot current density of the machine with in-slot cooling can be boosted to over 30 A_{rms}/mm^2, which allows for a higher power density for the machine. When combined with proposed in-slot heat exchanger cooling, PCB windings are shown that they can achieve superior slot current densities up to 20 A_{rms}/mm^2. Therefore, the proposed solution with PCB windings needs more attention for high power density and mass production of electric machines.

References

[1] S. A. Semidey and J. R. Mayor, "Experimentation of an electric machine technology demonstrator incorporating direct winding heat exchangers," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 10, pp. 5771–5778, Oct. 2014.

[2] A. Acquaviva, S. Skoog, and T. Thiringer, "Design and verification of in-slot oil-cooled tooth coil winding PM machine for traction application," *IEEE Transactions on Industrial Electronics*, vol. 68, no. 5, pp. 3719–3727, May 2021.

[3] A. Reinap, F. J. Marquez-Fernandez, M. Alakula, R. Deodhar, and K. Mishima, "Direct conductor cooling in concentrated windings," in *XIII International Conference on Electrical Machines (ICEM)*, 2018, pp. 2654–2660.

[4] R. Wrobel and R. J. McGlen, "Opportunities and challenges of employing heat-pipes in thermal management of electrical machines," in *International Conference on Electrical Machines (ICEM)*, 2020, pp. 961–967.

[5] R. Wrobel and D. Reay, "A feasibility study of heat pipes for thermal management of electrical machines," in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2020, pp. 4230–4237.

[6] C. Dong, Y. Qian, Y. Zhang, X. Hu, and W. Zhuge, "Coupled thermal-electromagnetic parametric modeling of permanent magnet machine based on flat heat pipe cooling," in *23rd International Conference on Electrical Machines and Systems (ICEMS)*, 2020, pp. 1689–1694.

[7] M. Galea, C. Gerada, T. Raminosoa, and P. Wheeler, "A thermal improvement technique for the phase windings of electrical machines," *IEEE Transactions on Industry Applications*, vol. 48, no. 1, pp. 79–87, Jan. 2012.

[8] M. Groninger, F. Horch, A. Kock, M. Jakob, and B. Ponick, "Cast coils for electrical machines and their application in automotive and industrial drive systems," in *4th International Electric Drives Production Conference (EDPC)*, 2014, pp. 1–7.

[9] A. Reinap, F. J. Marquez-Fernandez, R. Andersson, C. Hogmark, M. Alakula, and A. Goransson, "Heat transfer analysis of a traction machine with directly cooled laminated windings," in *4th International Electric Drives Production Conference (EDPC)*, 2014, pp. 1–7.

[10] M. Schiefer and M. Doppelbauer, "Indirect slot cooling for high-power-density machines with concentrated winding," in *IEEE International Electric Machines & Drives Conference (IEMDC)*, 2015, pp. 1820–1825.

[11] W. Sixel, M. Liu, G. Nellis, and B. Sarlioglu, "Cooling of windings in electric machines via 3-D printed heat exchanger," *IEEE Transactions on Industry Applications*, vol. 56, no. 5, pp. 4718–4726, Sep. 2020.

[12] W. Sixel, M. Liu, G. Nellis, and B. Sarlioglu, "Ceramic 3-D printed direct winding heat exchangers for thermal management of concentrated winding electric machines," *IEEE Transactions on Industry Applications*, vol. 57, no. 6, pp. 5829–5840, Nov. 2021.

[13] R. Wrobel and A. Hussein, "A feasibility study of additively manufactured heat guides for enhanced heat transfer in electrical machines," *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 205–215, Jan. 2020.

[14] C. Wohlers, P. Juris, S. Kabelac, and B. Ponick, "Design and direct liquid cooling of tooth-coil windings," *Electrical Engineering*, vol. 100, no. 4, pp. 2299–2308, Dec. 2018.

[15] F. Wu and A. M. EL-Refaie, "Additively manufactured hollow conductors integrated with heat pipes: design tradeoffs and hardware demonstration," in *International Conference on Electrical Machines (ICEM)*, 2020, pp. 52–58.

[16] F. Wu and A. M. EL-Refaie, "Additively manufactured hollow conductors with integrated cooling for high specific power electrical machines," in *International Conference on Electrical Machines (ICEM)*, 2020, pp. 1497–1503.

[17] A. Hembel and B. Sarlioglu, "PCB winding for electric machines with integrated 3D printed heat exchanger," in *International Transportation Electrification Conference (ITEC)*, Anaheim, CA, USA, 2022.