



BACHELORARBEIT

Natural air convection for cooling of particle accelerator electromagnets: case studies at CERN

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Abstract

Cooling by natural convection is investigated on two air-cooled corrector magnets at CERN. The heat transfer coefficient (HTC) for each magnet is estimated analytically using established empirical correlations for certain geometries. The HTC is also estimated numerically with three-dimensional steady-state finite element simulations. Air convection around the respective coils as well as heat conduction inside the coils are modelled. Different formulas for the HTC are tested in the post-processing of the simulation results. The HTC for each magnet is then determined experimentally by measuring surface temperatures on the coils through time at constant currents. A method to extract the HTC from these temperature curves is developed, in which the curves are fitted to a function that is derived from a thermodynamical analysis of the heating process. Some plausible ranges for the HTC for each magnet for different currents are obtained. The results of the different estimation methods are compared with the experimental results of the HTC.

Zusammenfassung

Kühlung durch natürliche Konvektion wird an zwei luftgekühlten schwachen Ablenkmagneten (sog. "corrector magnets") im CERN untersucht. Der Wärmeübergangskoeffizient (WÜK) wird für jeden Magneten durch etablierte empirische Beziehungen für bestimmte Geometrien abgeschätzt. Der WÜK wird auch mit Hilfe von dreidimensionalen, stationären Finite-Elemente-Simulationen numerisch abgeschätzt. Konvektion mit Luft um die entsprechenden Spulen sowie Wärmeleitung innerhalb der Spulen werden modelliert. Anhand der Simulationsergebnisse werden unterschiedliche Berechnungen des WÜK geprüft. Der WÜK für jeden Magneten wird dann experimentell bestimmt, indem Oberflächentemperaturen auf den Spulen bei konstanten elektrischen Strömen mit der Zeit gemessen werden. Eine Methode, den WÜK aus diesen Temperaturverläufen zu erhalten, wird entwickelt. Hierbei werden die Verläufe an eine Funktion angepasst, die aus einer thermodynamischen Analyse des Wärmeprozesses hergeleitet wird. Es werden plausible Wertebereiche für den WÜK jedes Magneten für verschiedene elektrische Ströme ermittelt. Die Ergebnisse der verschiedenen Abschätzungsmethoden werden mit den experimentellen Ergebnissen verglichen.

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Symbols and Abbreviations

Symbols

Note: The equivalent name and symbol in German literature is mentioned for selected items.

α	thermal diffusivity	Temperaturleitfähigkeit (a)
μ	dynamic viscosity	dynamische Viskosität (η)
ν	kinematic viscosity	kinematische Viskosität
ρ	density	
A_{sec}	conductor cross section	
c_p	specific heat capacity	spezifische Wärmekapazität
g	standard gravity	Normfallbeschleunigung
h	heat transfer coefficient	Wärmeübergangskoeffizient (α)
I_{RMS}	RMS (effective) current	QMW Strom (Effektivwert) (I_{eff})
k	thermal conductivity	Wärmeleitfähigkeit (λ)
Nu	NUSSELT number	
Pr	PRANDTL number	
$R_{20^\circ\text{C}}$	electrical resistance at 20°C	
Ra	RAYLEIGH number	
T_∞	free stream temperature	Fluid-/Umgebungstemperatur
T_S	surface temperature	Oberflächentemperatur
V	voltage	Spannung (U)

Abbreviations

AC	alternating current
CAD	computer-aided design
CEL	CFX Expression Language
DC	direct current
DS	Domain Size (sensitivity analysis)
H+V	combined horizontal and vertical planes (in the context of corrector magnets)
H	horizontal plane (in the context of corrector magnets)
HTC	heat transfer coefficient
MR	Mesh Refinement (sensitivity analysis)
NORMA	Normal Conducting Magnets (section)
OF	oxygen-free (copper)
RMS	root mean square
TS	Timescale (sensitivity analysis)
V	vertical plane (in the context of corrector magnets)
VI	Virtual Instrument (LabView)

1. Introduction

Introduction to CERN

The European Organization for Nuclear Research, more famously known as CERN, is an international scientific institution which is leading the world in high-energy physics research and is based in Geneva, Switzerland. Its complex chain of accelerators (illustrated in Figure 1.1) culminates in the Large Hadron Collider (LHC), the world's most powerful particle collider.

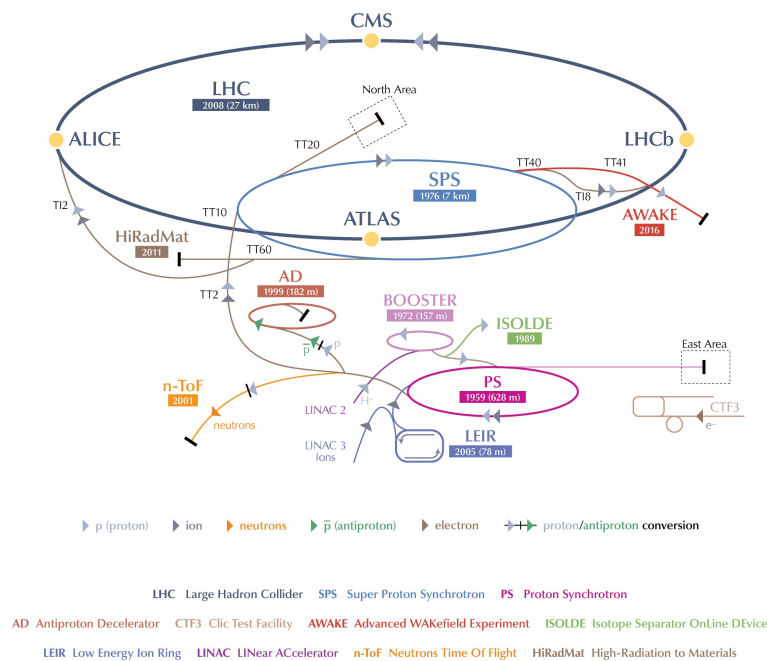


Figure 1.1: Diagram of the CERN accelerator complex¹

This institution, being academically oriented, offers various learning opportunities for young scientists, both at the undergraduate level and for higher career levels. This work was accomplished within the framework of one such opportunity, the Technical Student programme. The author spent six months at the Magnets Normal Conducting (MNC) section at CERN, three of which were used to write the present thesis.

¹Note: Adapted from <https://cds.cern.ch/record/1621583/files/CERN%27s-accelerator-complex2013.jpg> by F. Marcastel, 2013. Copyright 2013 by CERN.

Introduction to Particle Accelerator Magnets

Electrical magnets (magnets that consist of conductor coils rather than permanent magnets) play a central role in the way a particle accelerator works. Besides being adjustable (through the input current), they can be employed to for example deflect or focus a beam of charged particles by taking advantage of the LORENTZ force.

A magnet's function is determined by the topology of its field. Different field topologies, on the other hand, are caused by different numbers of magnetic poles (dipole, quadrupole, sextupole, etc.) and by the pole shape, among other factors. A homogenous vertical magnetic field between two magnetic poles, for example, bends a charged particle's trajectory horizontally (see Figure 1.2, left). A symmetric field created by four poles, on the other hand, focuses a beam of charged particles, since its components compensate for each other exactly in the middle (where the field is zero) and it grows stronger the further away a point is from the exact centre (see Figure 1.2, middle).

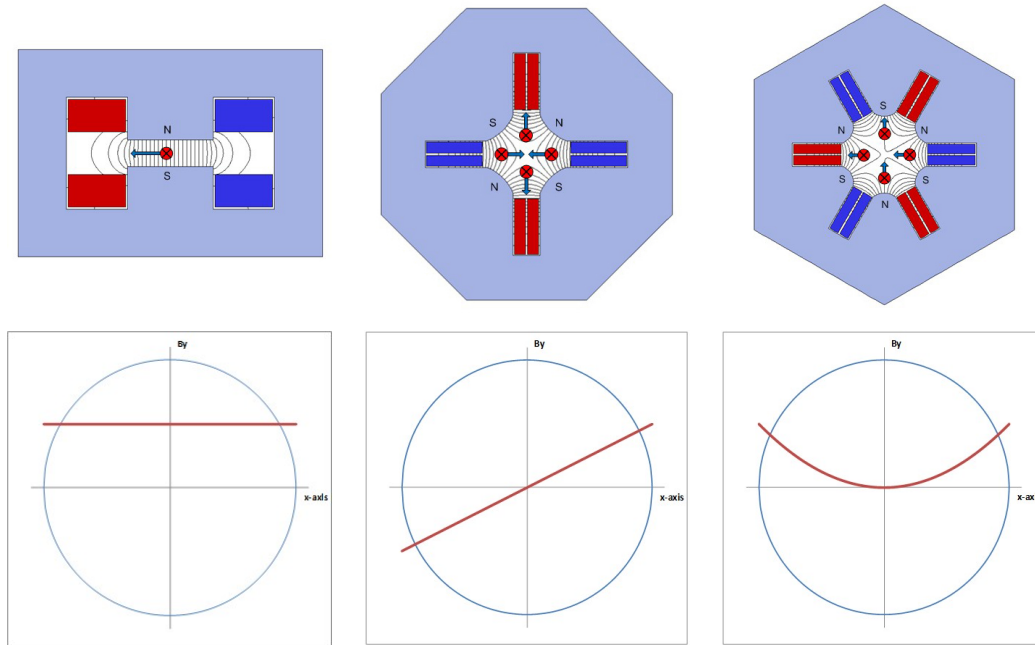


Figure 1.2: Illustration of the field topology and its effects on charged particles for a dipole, a quadrupole and a sextupole (top) and corresponding qualitative graph of the vertical magnetic field component B_y as a function of the horizontal distance x (bottom)²

As the magnets are expected to generate increasingly stronger magnetic fields (in order to control particles that are accelerated to higher energy levels), the coils which produce them will generate more and more heat because of their associated electrical resistance. Depending on the strength of the intended magnetic field, then, magnets can be air-cooled (through natural convection), water-cooled (through heat exchange with a fluid) or cryogenically cooled (rendering them superconducting and generating no heat losses in DC operation).

The magnets discussed in this work are air-cooled correctors. This group of magnets is a type of dipole, since it makes small corrections to a charged beam's trajectory. Correctors

²(T. Zickler, personal communication, January 5, 2015)

can bend horizontally, vertically or both. A vertical (V) corrector is shown in Figure 1.3(b), and two horizontal and vertical (H+V) correctors are shown in Figures 1.3(a) and 1.3(c).

The complex process of designing a magnet involves many different variables and physical effects. To help in the decision about one of many aspects, the cooling system, engineers have devised some "rules of thumb" for determining the most adequate one, depending on the effective current density J_{RMS} in the coil conductor. According to TOMMASINI (2011), for example, the current density in air-cooled magnets is usually around 1 A/mm^2 , while ZICKLER (2010, p. 92) sets it between 1 and 2 A/mm^2 .

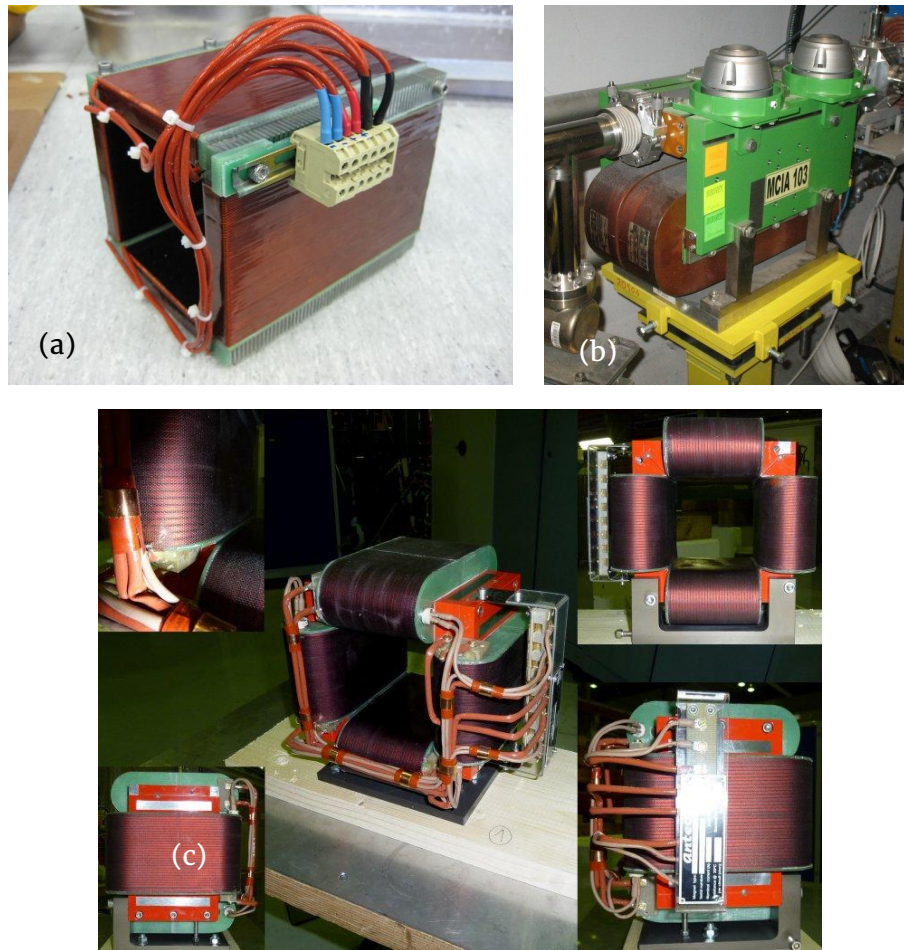


Figure 1.3: Some examples of air-cooled correctors at CERN³

However, magnets can have very different geometries, even if they are part of the same group, as is the case with air-cooled correctors. Figure 1.3 demonstrates this. Characteristics like the conductor cross-section and its form or the number of turns and layers can vary greatly, which influences the efficiency of the heat dissipation process. This constitutes a reason not to base considerations about cooling solely on fixed current density values (which contain no information about geometry).

Another challenge in the design of air-cooled magnets is the uncertainty associated with

³(a) *PXMCCAFWAP.jpg*. Retrieved from https://norma-db2.web.cern.ch/cern_norma/magnet/idcard/?id=3142.

(b) Adapted from *HCMCIA_001.jpg*. Retrieved from https://norma-db2.web.cern.ch/cern_norma/magnet/idcard/?id=7210.

(c) *PXMCCAQWAC.jpg*. Retrieved from https://norma-db2.web.cern.ch/cern_norma/magnet/idcard/?id=7088.

the heat transfer coefficient (HTC). This coefficient is of course indispensable when dealing with convective heat transfer. However, its empirical nature greatly hinders reliable temperature predictions, especially when coil geometries (and therefore their associated HTCs) can vary so much.

This work looks at the relationships between current densities and temperatures, taking into account different coil and magnet geometries. Some reference HTC values will be provided for these geometries. Another objective will be the comparison of different estimation methods for the HTC (analytical and numerical) with data retrieved from measurements performed by the author in selected cases.

Some Statistics About Corrector Magnets at CERN

The MNC (Magnets Normal Conducting) section at CERN has collated information and documentation about every normal-conducting magnet in the accelerators in the so-called NORMA database (it is currently only accessible through the CERN network). In order to obtain a general picture of the correctors at CERN and understand how they are designed, inquiries were done into this database.

Every magnet has its own identification number and is listed individually in the database, so different items might belong to the same magnet design. The item page then includes a summary of the general characteristics of the magnet (like its location, function or cooling system) and a section linking to all documents concerning the magnet (design and certification documents, for example).

Of special interest were the current density values of each magnet and their cooling system, in order to observe up to which current density air-cooling is applied in practice. The current density is usually not given directly, so it was calculated by dividing the RMS current⁴ I_{RMS} by the conductor cross section. Correctors with the following cooling systems were considered: air cooling, indirect water cooling (with an external water circuit) and water cooling (with water circulating through a duct inside the conductor itself). Indirect cooling was relevant since it represents the transition from air cooling to water cooling. To observe this same transition, only the three water-cooled magnet designs with the lowest current densities were selected.

The following central characteristics were recorded for each selected magnet:

- cooling system
- I_{RMS}
- conductor cross section dimensions (in order to obtain the cross section A_{sec})
- $R_{20^\circ\text{C}}$, electrical resistance at 20°C per coil

It must be mentioned that some magnets in this database are up to fifty years old (and still working reliably), which also means that the way the magnets are documented can vary considerably. In order to gather data as consistently as possible and make the designs comparable, only the magnets that presented information about the aforementioned central characteristics were selected.

⁴The RMS current enables a direct comparison between magnets that are operated in different modes (like a pulsed current and a direct current). The I_{RMS} value of a periodic current is equivalent to the direct current that would result in the same average power.

All in all, this meant

- 15 out of 42 designs of air-cooled correctors (784 items)
- 3 out of 7 designs of indirect cooling correctors (64 items)
- 3 out of 42 designs of water-cooled correctors (342 items)

were selected.

The input power (at 20°C) could furthermore be determined from the I_{RMS} value and the resistance at 20°C using OHM's law:

$$P = V \cdot I_{\text{RMS}} = R_{20^\circ\text{C}} \cdot I_{\text{RMS}}^2 \quad (1.1)$$

The conductor used in all the recorded magnets was copper. The average current density was 1.18 A/mm² for the air-cooled designs and 1.80 A/mm² for indirect cooling, while the lowest current density for water cooling was 4.60 A/mm². While these values confirm that indirect cooling covers the transition from less powerful magnets to more powerful ones, there seems to be a wide gap between water-cooled designs and the other two. This again becomes evident in Figure 1.4.

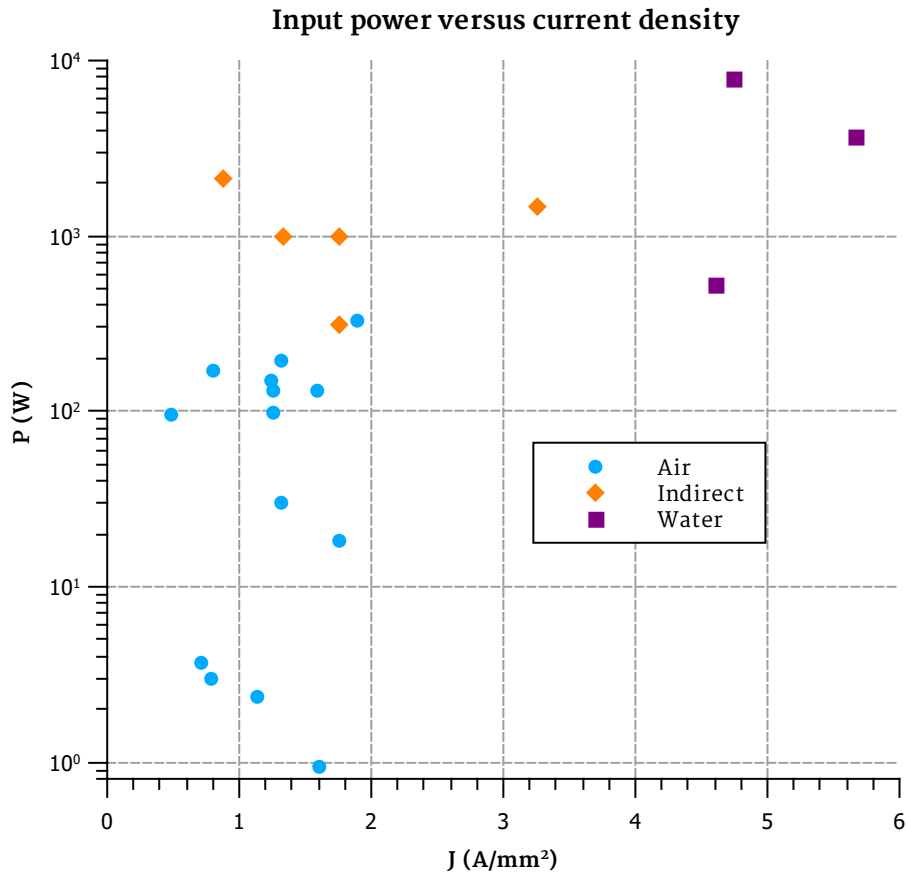


Figure 1.4: Scatter plot of the input power against the current density according to cooling system (on a logarithmic scale).

Here, with the exception of one point, there is a large gap between the current density points for air and indirect cooling and those for water cooling, which represent the lowest

registered current densities in these designs. This may be interpreted as a desire to stay within safe limits regarding cooling, or it may be that this current density range (and therefore magnetic field) is in fact generally not required. It is also worth noting how the switch to water cooling suddenly offers much more flexibility in terms of power choice.

The typical current density values for air cooling established by ZICKLER and TOMMASINI of 1 to 2 A/mm² are also confirmed by Figure 1.4.

Figure 1.5 investigates the relationship between current densities and the geometry of the coils. The ordinate axis corresponds to the number of conductor layers in the horizontal direction, thus giving a measure of the coil's thickness, and the abscissa axis corresponds to the conductor cross section. The area of each circle is proportional to the respective current density.

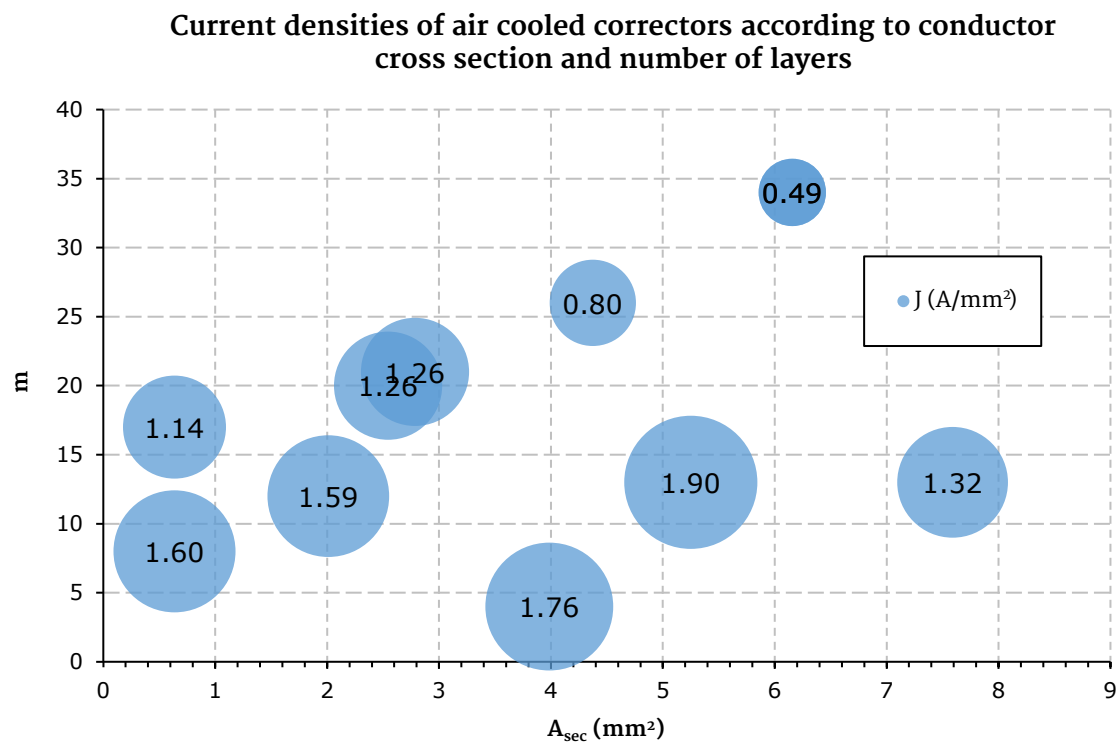


Figure 1.5: Bubble chart of the current density of air-cooled correctors according to conductor cross section and number of layers.

ZICKLER (2010, p. 92) specifies that the maximal current density should be 2 A/mm² for "small, thin coils" and 1 A/mm² for "voluminous coils which are almost entirely enclosed in the magnet yoke". Figure 1.5 supports the possibility that these rules are being applied in reality, once again despite the limited sample size (only the designs that included information about the number of layers could be used). The closer a point is to the origin of the graph, the thinner a coil will be. Conversely, a coil will be thicker the closer a point is to the opposite corner. The positions of the current densities in the graph therefore fit in well with these limits.

Overview of the Correctors Subjected to Study

Based on the survey of the NORMA database, two air-cooled magnets were selected to be the objects of this work. An effort was made to pick correctors with very different geometries and current densities, and keeping the constraint of having spare units available for testing in mind.

1.4.1 PXMCCA JWAP

PXMCCA JWAP is a two-plane (H+V) corrector magnet designed for a linear accelerator (Linac4) that will replace Linac2 at the beginning of the CERN proton accelerator chain. The coils are wound from oxygen-free copper conductor coated with a temperature-resistant coating (0.05 – 0.1 mm thickness on each side), and the winding is covered in vacuum-impregnated epoxy resin (1 – 8.3 mm thickness, depending on the place). All four coils are identical. The two coils in each plane are connected in series. The two different planes can be supplied separately. The coil yoke is made of electrical steel of the type EBG M270-50A.

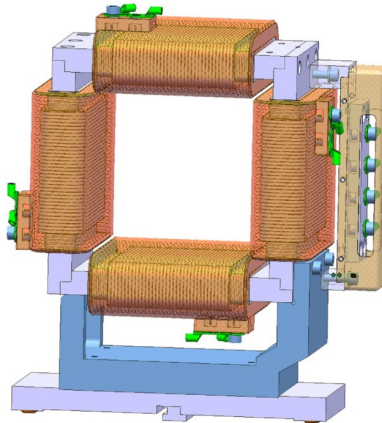


Figure 1.6: Computer-generated image of the PXMCCA JWAP corrector magnet⁵.

The concrete model being investigated was the PXMCCA JWAP-DA013205. The main characteristics of this magnet can be seen in Table 1.1.

1.4.2 HCMCIA

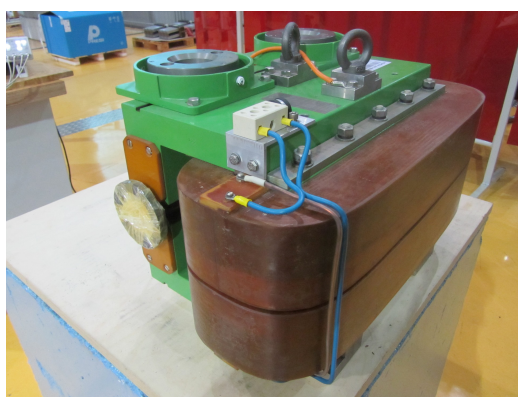
The HCMCIA is a horizontal (H) corrector magnet employed in two beam transfer lines from the Super Proton Synchrotron (SPS) to the Large Hadron Collider (LHC). It consists of two coils and two laminated half-cores. The coils are once again wound from copper conductor with an insulating coating and cast in epoxy resin. The magnet can be seen in Figure 1.7.

The designation of the model that was used for study is HCMCIA_001-BI000047. Its main characteristics are listed in Table 1.2.

⁵Retrieved from <https://edms.cern.ch/file/1165034/0.2/L4-MC-ES-0004-00-20.pdf>.

Table 1.1: Main parameters of the PXMCCAJWAP corrector magnet

Type	H+V corrector, laminated, air-cooled
Total magnet length	120 mm
Total magnet width×height	178 mm × 178.8 mm
Conductor material	OF copper
Conductor cross section	1.923 mm ²
Total number of turns per coil	224
Conductor length per coil	53.56 m
RMS current (in pulse mode at 10 Hz)	1.52 A
RMS current density	0.79 A/mm ²
Total resistance at 20 °C ⁶	2.357 Ω
Construction year	2014

**Figure 1.7:** Photograph of the HCMCIA corrector magnet.**Table 1.2:** Main parameters of the HCMCIA corrector magnet

Type	H corrector, laminated, air-cooled
Total magnet length	615 mm
Total magnet width×height	400 mm × 415 mm
Conductor material	copper
Conductor cross section	4.374 mm ²
Total number of turns per coil	1014
RMS current	3.5 A
RMS current density	0.80 A/mm ²
Total resistance at 20 °C ⁷	9.92 Ω
Construction year	2002

⁶Measured value from the certification document of the PXMCCAJWAP-DA013205.

⁷Measured value from the certification document of the HCMCIA_001-BI000047.

2. Analytical Estimations

Some empirical correlations for typical geometries have been devised to help determine the HTC, depending on the fluid properties and flow conditions of a certain free convection problem. The quantities being correlated are the NUSSELT number and the RAYLEIGH number, which are defined as

$$\overline{Nu}_L = \frac{\bar{h}L}{k} \quad \text{and} \quad Ra_L = \frac{g \beta (T_S - T_\infty) L^3}{\nu \alpha},$$

wherein k , ν and $\alpha = \frac{k}{\rho c_p}$ are all fluid properties. Both numbers are bound to a characteristic length L of the geometry. Air, the fluid in the present problem, will be treated as an ideal gas, so that the expansion coefficient β corresponds to the inverse of the absolute temperature (BERGMAN, LAVINE, INCROPERA, & DEWITT, 2011, p. 598).

For an external flow, the relationship between the NUSSELT and the RAYLEIGH numbers generally assumes the form (BERGMAN et al., 2011, p. 604)

$$\overline{Nu}_L = C Ra_L^n.$$

By determining the coefficients C and n empirically and substituting all the relevant fluid properties, it is thus possible to find $\bar{h}$, i.e. the average HTC for the geometry concerned. The geometries for which such correlations exist include the vertical plate, the horizontal plate and the long horizontal cylinder. For the problem at hand, the geometry of a coil will be reduced and approximated to these simple geometries. These correlations are moreover only valid for isothermal objects, so it will additionally be assumed that the coils in this problem become isothermal in steady-state.

All necessary fluid properties must be evaluated at the film temperature (BERGMAN et al., 2011, p. 605)

$$T_f = \frac{T_S + T_\infty}{2}$$

and the expansion coefficient will be $\beta = \frac{1}{T_f}$.

The problem of finding $\bar{h}$ is solved here iteratively. An initial guess about the surface temperature T_S (or the temperature difference ΔT) is made, to calculate the RAYLEIGH number and to evaluate the fluid properties. Using the resulting $\bar{h}$ after a first computation and NEWTON's law of cooling

$$\dot{Q} = h \cdot A \cdot \Delta T,$$

and if the average steady-state heat flux is known, a new ΔT can be found. This new temperature difference can then be reintroduced into the empirical model and deliver a new $\bar{h}$. This process can then be repeated until both $\bar{h}$ and ΔT converge, assuming the

initial ΔT guess is not too inaccurate and the fluid properties do not vary much in a small temperature interval (since a new T_S will influence the film temperature T_f at which they should be evaluated).

The free stream (room) temperature T_∞ will be set at 21°C.

2.1 PXMCCA JWAP

The vertical and horizontal coils will be considered separately. It will conservatively be assumed that the inside surfaces of the coils are adiabatic.

2.1.1 Vertical Coils

The model that is closest to the geometry of the vertical coil is the *vertical plate* model. Since the top and bottom surfaces of the coil are relatively small in comparison with the side surface (see Figure 2.1), only the HTC associated with the latter will be considered.

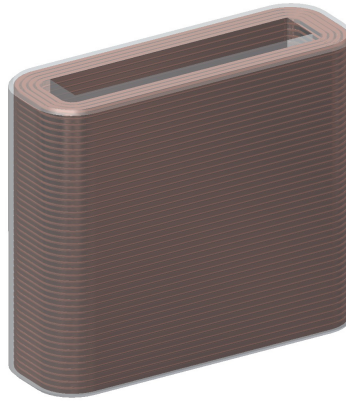


Figure 2.1: CAD model of a PXMCCA JWAP coil.

The characteristic length in the *vertical plate* model is the height of the plate, which here corresponds to the height of the coil. Therefore

$$L = 101 \text{ mm} .$$

The following vertical plate correlation for laminar flow ($Ra_L \lesssim 10^9$) will be used (BERGMAN et al., 2011, p. 605), since laminar flow can be expected for a natural convection problem:

$$\overline{Nu}_L = 0.68 + \frac{0.670 Ra_L^{\frac{1}{4}}}{\left(1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}} , \quad (2.1)$$

with the PRANDTL number $Pr = \frac{\nu}{\alpha}$. An initial guess of the temperature difference will be made of 5 K, i.e. $T_S = 26^\circ\text{C}$. The film temperature is therefore

$$T_f = \frac{T_S + T_\infty}{2} = 23.5^\circ\text{C} .$$

The fluid properties for air at this temperature and standard pressure are, according to Wolfram Alpha LLC (2015b, 2015e and 2015h):

$$k = 0.0261 \frac{\text{W}}{\text{m K}}, \quad \rho = 1.19 \frac{\text{kg}}{\text{m}^3}, \quad c_p = 1006 \frac{\text{J}}{\text{kg K}}, \quad \nu = 1.524 \cdot 10^{-5} \frac{\text{m}^2}{\text{s}}.$$

The expansion coefficient and the thermal diffusivity become:

$$\beta = \frac{1}{T_f} \approx 0.0034 \frac{1}{\text{K}}, \quad \alpha = \frac{k}{\rho c_p} \approx 2.180 \cdot 10^{-5} \frac{\text{m}^2}{\text{s}}.$$

With the standard gravity acceleration $g = 9.81 \text{ m/s}^2$, the RAYLEIGH number for these flow conditions is thus

$$Ra_L = \frac{g \beta (T_S - T_\infty) L^3}{\nu \alpha} \approx 5.125 \cdot 10^5,$$

which confirms that this is a laminar flow. $\overline{Nu}_L$ can now be determined by substituting this result and the definition equation of the PRANDTL number:

$$\overline{Nu}_L = 0.68 + \frac{0.670 Ra_L^{\frac{1}{4}}}{\left(1 + \left(\frac{0.492}{\frac{\nu}{\alpha}}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}} \approx 14.415.$$

Finally, by rearranging the definition of the NUSSELT number, the HTC is obtained:

$$\bar{h} = \frac{k \overline{Nu}_L}{L} = 3.73 \frac{\text{W}}{\text{m}^2 \text{K}}.$$

As described earlier, this process was repeated iteratively using a Matlab function (see Appendix A.1). The function is summarised in Figure 2.2. Two additional parameters were required for this computation: the steady-state dissipated power P_{diss} and the surface available for convective heat transfer A_{free} .

All the electrical power that is introduced into the thermodynamic system of the coil must leave the system in the form of heat, since the steady-state case is being considered. This power can be calculated using equation 1.1. For all estimations of the HTC a value of 1.4 A will be used for the RMS current. The electrical resistance of both vertical coils at 20°C, which are connected in series, was measured in the certification of the magnet at 1201 mΩ. The resistance of one vertical coil is thus 600.5 mΩ. This results in a dissipated power per coil of

$$P_{\text{diss}} = I_{\text{RMS}}^2 \cdot R_{20^\circ\text{C}} \approx 1.177 \text{ W}.$$

The free surface was determined using CAD software and the model of a coil. The inside of the coil (the surface that is in contact with the iron yoke) was assumed to be adiabatic. The free surface for one coil was then found to be

$$A_{\text{free}} \approx 35542 \text{ mm}^2.$$

After including all the required parameters in the Matlab function, the following converged values for the HTC and the temperature difference were returned:

$$\bar{h} \approx 4.16 \frac{\text{W}}{\text{m}^2 \text{K}} , \quad \Delta T \approx 8.0 \text{ K} .$$

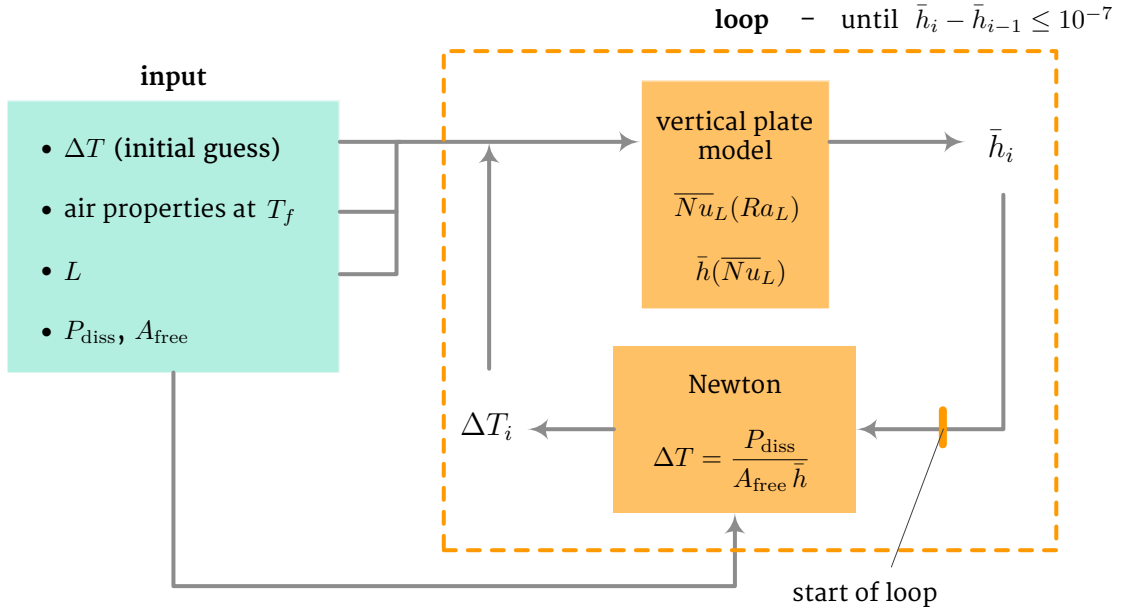


Figure 2.2: Schematic of the function devised to determine the HTC iteratively using the vertical plate correlation.

2.1.2 Horizontal Coils

For the horizontal coils, three different empirical correlations were chosen:

- upper surface of hot plate (USHP)
- lower surface of hot plate (LSHP)
- vertical plate (VP)

In this way the three estimated HTCs associated with the respective surfaces (illustrated in Figure 2.3) can be combined to find an average HTC, using a weighted average that takes the surface proportion into account. Again, the left and right side surfaces have been neglected as much smaller. The boundaries between the regions were set on the middle of the round corners (the dashed yellow line in Figure 2.3).

The characteristic length for the USHP and the LSHP models is defined as

$$L = \frac{A_S}{P} ,$$

with the plate surface area A_S and the plate perimeter P , in order to take different plate shapes into account (BERGMAN et al., 2011, p. 609). All of the following geometric quantities were determined using CAD software. Both the USHP and the LSHP surfaces have the following dimensions, since both sides of the coil are identical:

$$A_S \approx 11052 \text{ mm}^2 , \quad P \approx 283.6 \text{ mm} .$$

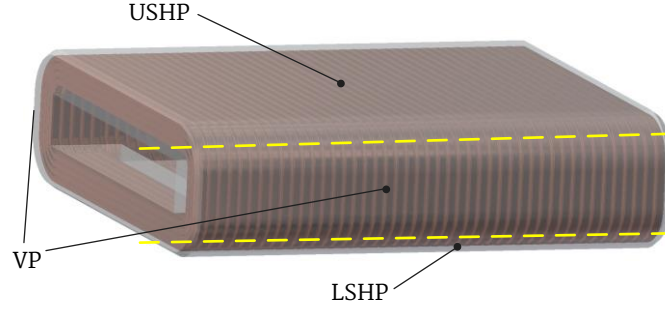


Figure 2.3: Assignment of empirical correlation models to the horizontal coil surfaces of the PXMCCAJWAP.

The characteristic length (henceforth designated as L_m , for modified length) for both is therefore

$$L_m = \frac{A_S}{P} \approx 38.9 \text{ mm} .$$

The characteristic length for the VP surface, on the other hand, corresponds to the sum of the straight section along the height of the coil and half of the arc lengths in the corners, giving

$$L \approx 21.2 \text{ mm} .$$

The empirical correlations for the USHP and the LSHP are, respectively (BERGMAN et al., 2011, p 610),

$$\overline{Nu}_L = 0.54 Ra_L^{\frac{1}{4}} \quad (10^4 \lesssim Ra_L \lesssim 10^7, Pr \gtrsim 0.7) , \quad (2.2a)$$

$$\overline{Nu}_L = 0.52 Ra_L^{\frac{1}{5}} \quad (10^4 \lesssim Ra_L \lesssim 10^9) . \quad (2.2b)$$

The correlation for the VP was already mentioned in equation 2.1.

The initial guess for the temperature difference will be kept (5 K), and the same air properties therefore apply. The RAYLEIGH number for the USHP and LSHP regions is consequently

$$Ra_{L,SHP} = \frac{g \beta (T_S - T_\infty) L_m^3}{\nu \alpha} \approx 4.689 \cdot 10^4$$

and the PRANDTL number is

$$Pr = \frac{\nu}{\alpha} \approx 0.70 ,$$

which means that equations 2.2a and 2.2b may be employed. The RAYLEIGH number for the VP region is

$$Ra_{L,VP} = \frac{g \beta (T_S - T_\infty) L^3}{\nu \alpha} \approx 7.549 \cdot 10^3 .$$

By undergoing the same steps as with the vertical coil, the following first estimates for the HTC are obtained:

$$\bar{h}_{USHP} \approx 5.32 \frac{\text{W}}{\text{m}^2 \text{K}} , \quad \bar{h}_{LSHP} \approx 2.99 \frac{\text{W}}{\text{m}^2 \text{K}} , \quad \bar{h}_{VP} \approx 6.73 \frac{\text{W}}{\text{m}^2} .$$

To draw a weighted average of these three local coefficients, the respective surfaces must be determined. In the case of the USHP and the LSHP regions the surface was already

necessary for calculating the modified characteristic length, and is thus A_S . The surface of the VP region is

$$A_{VP} \approx 6620.2 \text{ mm}^2 .$$

The average HTC for the whole coil can now be computed:

$$\bar{h} = \frac{A_S \cdot \bar{h}_{USHP} + A_S \cdot \bar{h}_{LSHP} + A_{VP} \cdot \bar{h}_{VP}}{2A_S + A_{VP}} \approx 4.75 \frac{\text{W}}{\text{m}^2 \text{K}} .$$

As before, a Matlab function that feeds the temperature difference back into the HTC computation until both values stabilise was run (see Appendix A.1). The function is delineated in Figure 2.4.

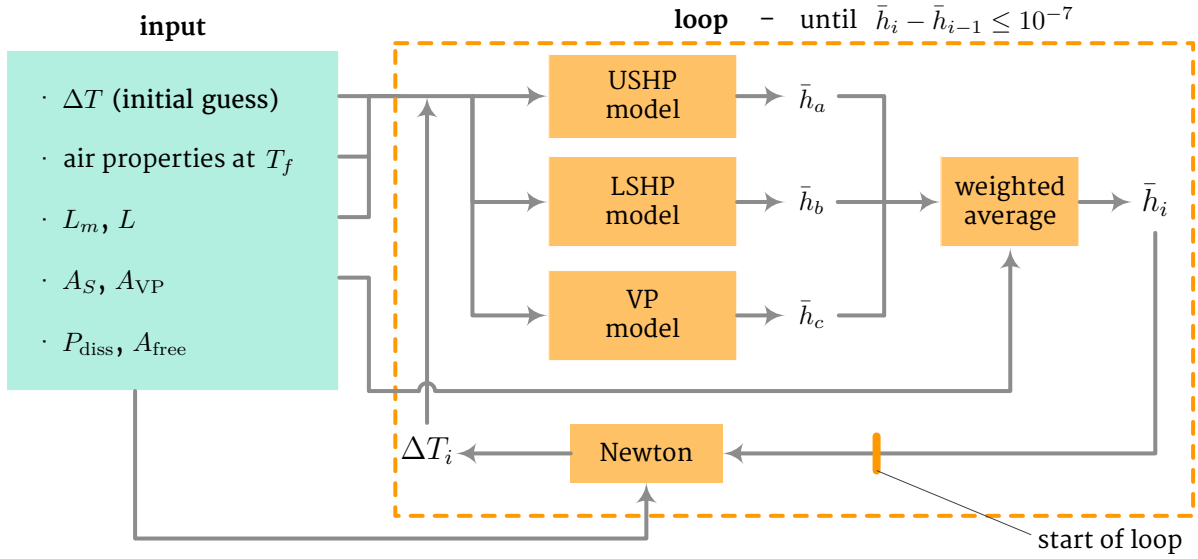


Figure 2.4: Schematic of the function devised to determine the HTC iteratively for the horizontal coils.

Since the horizontal plane has a slightly smaller measured resistance of $1156 \text{ m}\Omega$, i.e. $578 \text{ m}\Omega$ per coil, the dissipated power is in this case

$$P_{\text{diss}} = I_{\text{RMS}}^2 \cdot R_{20^\circ\text{C}} \approx 1.133 \text{ W} ,$$

with an RMS current of 1.4 A . The free surface is the same as was mentioned before, since the horizontal and vertical coils are identical.

After inserting these parameters, the function returned the following converged values:

$$\begin{aligned} \bar{h}_{\text{USHP}} &\approx 5.14 \frac{\text{W}}{\text{m}^2 \text{K}} , & \bar{h}_{\text{LSHP}} &\approx 2.91 \frac{\text{W}}{\text{m}^2 \text{K}} , & \bar{h}_{\text{VP}} &\approx 6.52 \frac{\text{W}}{\text{m}^2 \text{K}} , \\ \bar{h} &\approx 4.60 \frac{\text{W}}{\text{m}^2 \text{K}} , & \Delta T &\approx 8.0 \text{ K} . \end{aligned}$$

The resulting average HTC is similar to the one for the vertical coil.

2.2 HCMCIA

The two coils in the HCMCIA are mounted one above the other with a very small gap, so for the sake of simplicity they will be treated as a single coil (with twice the height of one coil). The top and bottom surfaces of one of the sides of the coils (the pink surfaces in Figure 2.5) are furthermore covered by the steel yoke, as well as the inner coil surfaces. These surfaces will be considered adiabatic. For the estimation of the HTC on the rest of the top and bottom surfaces (the purple surfaces in Figure 2.5), the *upper surface of hot plate* and the *lower surface of hot plate* models will be used, respectively. The *vertical plate* model will be applied to the side surfaces (yellow in Figure 2.5).

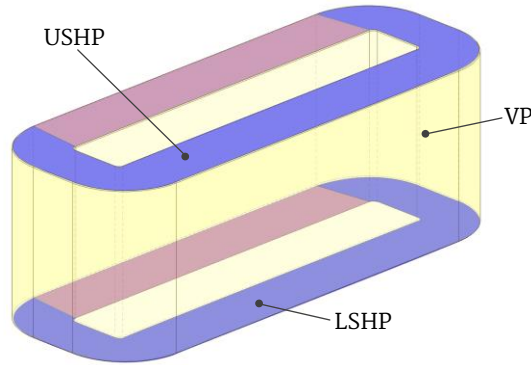


Figure 2.5: Assignment of empirical correlation models to the stacked coils of the HCMCIA.

Based on a CAD model of the "double coil", the plate surface area and perimeter are

$$A_S \approx 56274 \text{ mm}^2 \quad \text{and} \quad P \approx 1785.3 \text{ mm} ,$$

so that the characteristic length L_m of the *hot plate* models becomes

$$L_m = \frac{A_S}{P} \approx 31.5 \text{ mm} .$$

The characteristic length for the VP model is

$$L = 200 \text{ mm} .$$

The initial guess for the temperature difference will be 50 K ($T_S = 71^\circ\text{C}$), resulting in the film temperature

$$T_f = \frac{T_S + T_\infty}{2} = 46^\circ\text{C}$$

and the following air properties (Wolfram Alpha LLC, 2015c, 2015f and 2015i):

$$k = 0.0278 \frac{\text{W}}{\text{m K}} , \quad \rho = 1.106 \frac{\text{kg}}{\text{m}^3} , \quad c_p = 1007 \frac{\text{J}}{\text{kg K}} , \quad \nu = 1.769 \cdot 10^{-5} \frac{\text{m}^2}{\text{s}} .$$

The expansion coefficient and the thermal diffusivity are, for this film temperature,

$$\beta = \frac{1}{T_f} \approx 0.0031 \frac{1}{\text{K}} , \quad \alpha = \frac{k}{\rho c_p} \approx 2.496 \cdot 10^{-5} \frac{\text{m}^2}{\text{s}} .$$

The RAYLEIGH numbers of the *hot plate* models and the *vertical plate* model can now be determined, as well as the PRANDTL number.

$$Ra_{L,SHP} = \frac{g \beta (T_S - T_\infty) L_m^3}{\nu \alpha} \approx 1.090 \cdot 10^5$$

$$Ra_{L,VP} = \frac{g \beta (T_S - T_\infty) L_m^3}{\nu \alpha} \approx 2.784 \cdot 10^7$$

$$Pr = \frac{\nu}{\alpha} = 0.709$$

Using correlations 2.2a and 2.2b for the USHP and LSHP regions, respectively, and correlation 2.1 for the VP region, the respective NUSSELT numbers are obtained. By rearranging the definition equation of Nu_L , the average HTC associated with each of these regions is found to be

$$\bar{h}_{USHP} = \frac{k \cdot \overline{Nu}_{L,USHP}}{L} = 8.65 \frac{W}{m^2 K} ,$$

$$\bar{h}_{LSHP} = \frac{k \cdot \overline{Nu}_{L,LSHP}}{L} = 4.67 \frac{W}{m^2 K} ,$$

$$\bar{h}_{VP} = \frac{k \cdot \overline{Nu}_{L,VP}}{L} = 5.29 \frac{W}{m^2 K} .$$

To obtain the average HTC, a weighted average will be computed using the free surfaces associated with each region. For the USHP and the LSHP regions, these each correspond to A_S . The free surface of the VP region is

$$A_{VP} \approx 297103 \text{ mm}^2 .$$

The average HTC then becomes

$$\bar{h} = \frac{A_S \cdot \bar{h}_{USHP} + A_S \cdot \bar{h}_{LSHP} + A_{VP} \cdot \bar{h}_{VP}}{2 A_S + A_{VP}} \approx 5.66 \frac{W}{m^2 K} .$$

The iterative process described at the beginning of this chapter was once again carried out in the form of a Matlab function, presented in Appendix A.2. The function is identical to the one written for the PXMCCAJWAP horizontal coil and can also be grasped in Figure 2.4.

The function provided the following results:

$$\bar{h}_{USHP} \approx 8.73 \frac{W}{m^2 K} , \quad \bar{h}_{LSHP} \approx 4.70 \frac{W}{m^2 K} , \quad \bar{h}_{VP} \approx 5.33 \frac{W}{m^2 K} ,$$

$$\bar{h} \approx 5.63 \frac{W}{m^2 K} , \quad \Delta T \approx 51.9 \text{ K} .$$

3. Numerical Estimations

Another form of estimation is the numerical analysis, which will be described in the following. Three-dimensional steady-state simulations that modelled both heat conduction in solids as well as fluid behaviour in a fluid domain were carried out. The simulations were performed using *ANSYS CFX*. *CFX* is a fluid dynamics component of *ANSYS* that has its own pre-processing, solver and post-processing environment.

3.1 PXMCCA JWAP

A steady-state simulation of natural convection around each coil was conducted separately. The heat source corresponded to the copper region and both the initial and the free-stream temperature were set at 21°C. The simulations were conducted for a current of 1.4 A (used in the previous chapter), but also with 3.7 A and 6 A as the input current.

3.1.1 Geometric Model

The 3D model for each coil was designed with CAD software based on technical drawings of the PXMCCA JWAP. The CAD models represent only one quarter of the coils, in order to take advantage of two symmetry planes. Both models are depicted in Figure 3.1.

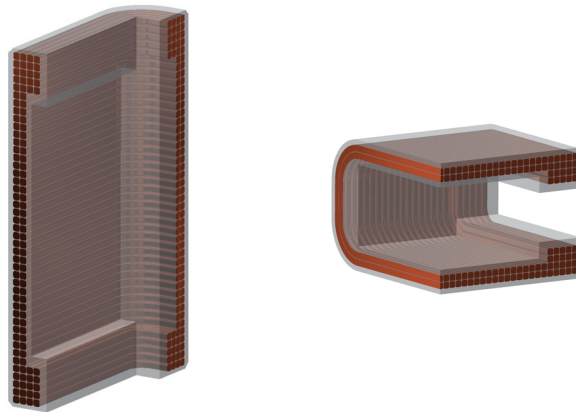


Figure 3.1: CAD models of the vertical (left) and horizontal (right) coils that were used for simulation.

For practical reasons, the winding of the conductor was not modelled as a continuous spiral, but as separate "rings" stacked on top of each other. The cross section of the coil looks nonetheless the same as it would if the conductor were continuously wound. The

coating around the conductor was not included in the model, since its very small thickness rendered it difficult to mesh. However, it was later included in the boundary set-up (see 3.1.3). The epoxy cast was designed around the wound conductor according to its dimensions in the technical drawings.

The air region (a box) was also included in the CAD model. For the dimensions of the box, the configuration in Figure 3.2 was taken as orientation.

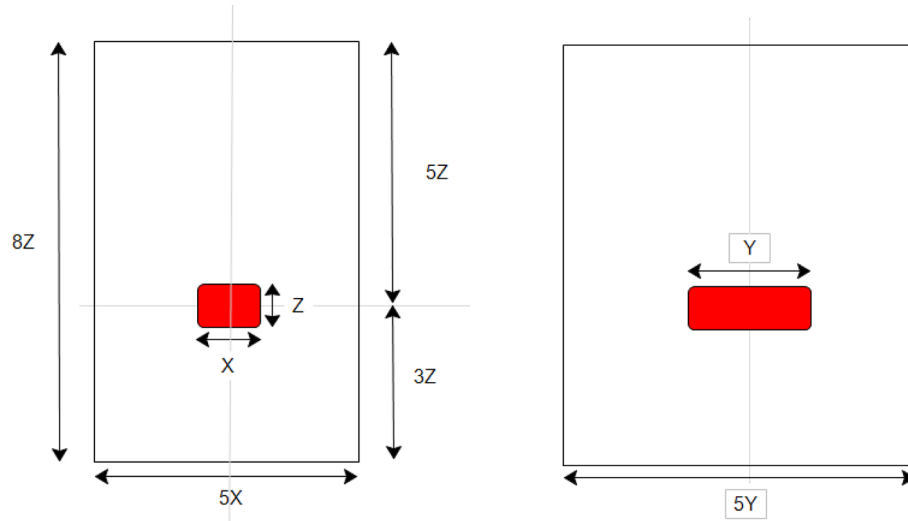


Figure 3.2: "Chimney" configuration for external natural convection¹.

By multiplying the overall dimensions of the "quarter-coil" by the factor 5 or 8, the air region in Figure 3.3 was generated (in the case of the horizontal coil).

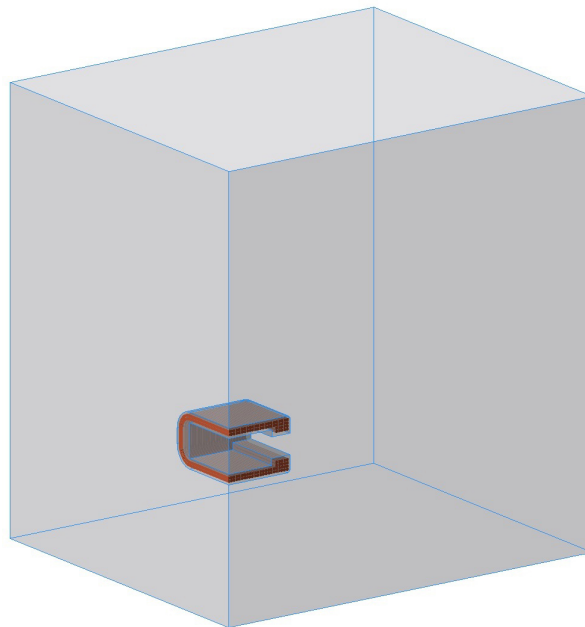


Figure 3.3: CAD model of the horizontal coil with the surrounding air region.

¹Note: Reproduced from *Help: External Natural Convection*, retrieved from <http://help.autodesk.com/view/SCDSE/2014/ENU/?guid=GUID-281ADD41-CC97-40E3-BE89-DE16A8C094F0>. Used under a Creative Commons Attribution-NonCommercial-ShareAlike 3.0 Unported (<http://creativecommons.org/licenses/by-nc-sa/3.0/>).

3.1.2 Mesh

To mesh the coils, the CAD file of each was imported into the *ANSYS Meshing* application. A three-dimensional mesh was created for each of the parts in the model (the copper, cast and air solids). Besides the normal patch-conforming algorithm with tetrahedrons or hexahedrons, *ANSYS Meshing* offers a much more efficient method called *Sweep*, though it is only applicable to some geometries.

As described by ANSYS, Inc. (2013d, p. 231), the *Sweep* method can be applied when an object has two topologically opposite identical surfaces, called the source and target faces. The algorithm creates a two-dimensional mesh with quadrilateral and triangular elements on the source face, copies it to the target face, and fills the space in between with hexahedral or wedge elements.

Mesh sizing (as well as other meshing tools) in *ANSYS Meshing* is highly automated. An *Advanced Size Function* can be activated which displays a range of sizing parameters and allows for more control over sizing. This function was activated for every mesh. But the refinement of the meshes was mainly adjusted through a *Mesh Control* called *Body Sizing*, where an *Element Size* can be defined for a given body. The mesher will then attempt to create elements around this dimension. In addition, all elements are quadratic elements.

One-level mesh refinement was always applied to the surface of the air region that is in contact with the outside of the cast (excluding the surfaces considered adiabatic), in order to enable a better resolution of fluid flow near the wall.

Vertical coil

In the vertical coil the *Sweep* method was applied to the copper body. The other two bodies were meshed with tetrahedrons. For the "Air" body an *Element Size* of 0.01 m was specified. Table 3.1 lists the number and type of generated elements for each domain, as well as the total number of elements of the resulting mesh. It is depicted in Figure 3.5(a) on p. 29.

Table 3.1: Mesh information for the vertical coil (PXMCCAJWAP).

Domain	Nodes	Elements	Tetrahedra	Wedges	Hexahedra
Air	42,494	228,560	228,560	0	0
Cast	618,023	2,755,200	2,755,200	0	0
Copper	247,660	171,180	0	360	170,820
All Domains	908,177	3,154,940	2,983,760	360	170,820

In order to evaluate the quality of the mesh, four parameters were taken as reference: *Minimum* and *Maximum Face Angle*, *Maximum Edge Length Ratio* and *Maximum Element Volume Ratio*. The *Face Angle* is calculated at the nodes between the faces that are connected to them and "can be considered to be a measure of skewness" (ANSYS, Inc., 2013a, p. 269). The *Edge Length Ratio* corresponds to the "longest edge of a face divided by the shortest edge of the face" and the *Element Volume Ratio* is the ratio of the maximum and the minimum volumes of the elements that touch a node (p. 270).

ANSYS Inc. presents some guidelines for these parameters in pp. 270–271, depending on the type of element. The problematic ranges are included in parentheses in Table 3.2, together with the calculated parameters for the mesh. The values that surpass the thresholds in parentheses are signified in red.

Table 3.2: Mesh quality indicators for the vertical coil (PXMCCA JWAP)

Domain	Element Type	Minimum Face Angle [°]	Maximum Face Angle [°]	Maximum Edge Length Ratio	Maximum Element Volume Ratio
Air	tetra.	6.39 (< 10)	140.26 (> 170)	8.93 (> 100)	35.16 (> 30)
Cast	tetra.	9.33 (< 10)	144.57 (> 170)	6.14 (> 100)	44.20 (> 30)
Copper	hexa., wedge	48.22 (< 10)	135.78 (–)	7.27 (> 100)	4.09 (> 5)

According to ANSYS, Inc., "the robustness of the CFX–Solver will not be adversely affected by high element volume ratios" (2013a, p. 271), though a high element volume ratio does affect accuracy. It must be borne in mind that the "Cast" domain is not easily meshed, so some mesh quality was sacrificed in exchange for the ability to accurately represent the complicated geometry of the cast in the simulation.

Horizontal coil

In the horizontal coil model no body fulfilled the geometric requirements to undergo the *Sweep* method, so all domains were meshed with tetrahedra. The *Element Size* in "Air" was once again set at 0.01 m, thereby conferring identical refinements to the horizontal and the vertical mesh. The resulting mesh can be seen in Figure 3.6(a) on p. 30. The general mesh information is listed in Table 3.3, and the quality indicators in Table 3.4.

Table 3.3: Mesh information for the horizontal coil (PXMCCA JWAP).

Domain	Nodes	Elements (Tetrahedra)
Air	52,719	281,876
Cast	358,127	1,540,201
Copper	350,352	1,386,810
All Domains	761,198	3,208,887

Table 3.4: Mesh quality indicators for the horizontal coil (PXMCCA JWAP).

Domain	Minimum Face Angle [°]	Maximum Face Angle [°]	Maximum Edge Length Ratio	Maximum Element Volume Ratio
Air	12.59 (< 10)	137.17 (> 170)	4.58 (> 100)	51.86 (> 30)
Cast	7.67 (< 10)	143.97 (> 170)	7.11 (> 100)	39.64 (> 30)
Copper	4.44 (< 10)	145.67 (> 170)	12.91 (> 100)	28.27 (> 30)

Once again the mesh displays some level of skewness and large volume differences between neighbouring elements. However, these shortcomings will be tolerated for the same reason that was described above.

3.1.3 Pre-Processing

The finished mesh was then imported into the pre-processing environment of CFX. *CFX-Pre* is where the *Domains*, *Boundaries*, *Domain Interfaces*, material properties, fluid models and solver settings are defined.

Domains and Materials

Three different domains were set up in this analysis: "Air", "Cast" and "Copper". To each domain a material with certain properties must be attributed.

Air material The *CFX-Pre* default material *Air Ideal Gas* was selected, so the density became a function of temperature and pressure according to the ideal gas law. The remaining necessary properties at 21°C (the free-stream temperature) and standard pressure were altered and taken from Wolfram Alpha LLC instead (2015a, 2015d and 2015g).

Cast material The physical properties of the resin cast were unknown. To cast the coils in the resin mould, the impregnation resin (of type Araldite F, according to the technical specification of the PXMCCAJWAP) has to be mixed with a curing agent, an accelerator and a hardener, which together constitute the casting system. A brochure for a casting system based on Araldite F epoxy resin was found, from which the density and thermal conductivity values for the finished cast could be inferred (Vantico Ltd., 2000, p. 5). The chosen specific heat capacity was based on RICHARDSON's values for cured epoxy resin (2005). The new material "Epoxy" was created.

Conductor coating material The exact material of the conductor coating is also not known. However, the technical specification mentions two coating types (Thermex[®] and Duroflex[®]). Some Von Roll Thermex[®] products seem to either include or be based on polyamide-imide (Von Roll Holding Ltd., n.d., pp. 8-9). It will therefore be assumed that the material of the coating is polyamide-imide (this will later be used in a boundary interface). The density and thermal conductivity values could be found in Wolfram Alpha LLC (2015j), while the specific heat capacity was averaged from the values given in "Solvay Specialty Polymers" (n.d.). "Polyamide imide" was added to the material library.

Conductor material The default material *Copper* was chosen from the material database and its properties adopted.

The chosen materials for each domain as well as polyamide-imide and their properties are detailed in Table 3.5.

Table 3.5: Materials used in the PXMCCAJWAP simulations and their properties, attributed to each domain.

<i>Domain</i>	Air	Cast	Copper	
<i>Material</i>	Air Ideal Gas	Epoxy	Copper	Polyamide imide
$\rho \left[\frac{\text{g}}{\text{cm}^3} \right]$	$\rho(T, P)$	1.85	8.933	1.47
$c_p \left[\frac{\text{J}}{\text{kgK}} \right]$	1006	1110	385	1240
$\lambda \left[\frac{\text{W}}{\text{mK}} \right]$	0.0259	0.85	401	0.4
$\mu \left[\text{Pa} \cdot \text{s} \right]$	$1.83 \cdot 10^{-5}$	–	–	–

The "Air" domain was specified as a fluid domain, and "Cast" and "Copper" as solid domains.

"Air" domain Buoyancy was activated for "Air", which means that the source term

$$S_{M,\text{buoy}} = (\rho - \rho_{\text{ref}}) g$$

is added to the momentum equations (ANSYS, Inc., 2013c, p. 35). The reference density (at 21°C) ρ_{ref} was defined with 1.2 kg/m^3 (Wolfram Alpha LLC, 2015d) and g with 9.81 m/s^2 . The density itself was a function of temperature and pressure (ideal gas law), since the material in the domain had been defined as an ideal gas. The chosen heat transfer model for this domain was *Thermal Energy*, which, as opposed to the *Total Energy* model, neglects kinetic energy effects and is therefore suitable for low speed flows (ANSYS Inc., 2013c, pp. 12–13). For this same reason the laminar model was applied.

"Copper" domain The "Copper" region was defined at the same time as an energy source. The input power was determined from the current (1.4 A, 3.7 A or 6 A) and the resistance of the coil. However, since the resistance changes with temperature, the following formula for the input power as a function of temperature was constructed:

$$P(T) = I_{\text{RMS}}^2 \cdot \frac{1}{8} \cdot R_{20^\circ\text{C}} \cdot (1 + \alpha_T (T - T_{20^\circ\text{C}})) ,$$

with $\alpha_T = 0.004041 \frac{1}{\text{K}}$ and the resistances for the horizontal and vertical planes taken from the certification document of the PXMCCAJWAP-DA013205 (mentioned on p. 14 and p. 11 respectively). The factor $1/8$ is due to the fact that $R_{20^\circ\text{C}}$ is the resistance for one plane, i.e. two coils, and only a fourth of each coil is represented in the model. T is in reality the volume average of the temperature in the "Copper" domain for each iteration, which means that P is not location-dependent.

Boundaries and Interfaces

After defining domains, *Boundaries* (surfaces) within these domains must be defined as well. Where these surfaces overlap (where two domains meet) and if there should be an interaction between the regions, a *Domain Interface* must additionally be defined.

In this analysis three types of CFX boundaries were used: the *Opening*, *Symmetry Plane* and *Wall* boundaries. The *Opening* boundary condition allows flow in and/or out of a domain (ANSYS Inc., 2013a, p. 87). A *Symmetry Plane* mirrors both the geometry and the flow of a domain to the other side of the boundary (ANSYS Inc., p. 98). A *Wall* boundary represents a barrier to fluid flow but allows the exchange of heat (ANSYS Inc., 2013c, p. 98).

The boundaries and interfaces are summarised in Table 3.6. Some details on selected boundaries follow.

Table 3.6: Boundaries and interfaces in the PXMCCAJWAP simulations.

Domain	Boundary	Type
Air	Air_opensurf	<i>Opening</i>
	Air_symsurf	<i>Symmetry Plane</i>
	Air_isolsurf	<i>Wall</i>
	Cast_Air Side 2	Fluid-Solid Interface
Cast	Cast_Air Side 1	Fluid-Solid Interface
	Cast_symsurf	<i>Symmetry Plane</i>
	Cast_isolsurf	<i>Wall</i>
	Copper_Cast Side 2	Solid-Solid Interface
Copper	Copper_Cast Side 1	Solid-Solid Interface
	Copper_symsurf	<i>Symmetry Plane</i>

"Air_opensurf" The *Mass and Momentum* option *Opening Pres. and Dirn* was selected, which requires that a *Relative Pressure* and a *Flow Direction* be specified. The relative pressure was defined as being non-existent (0 Pa), since this is a natural convection problem and no initial air flow should be present.

For the flow direction the option *Normal to Boundary Condition* was chosen. The other options entailed defining concrete velocity components. Though the *Normal to Boundary Condition* is admittedly unrealistic on the side surfaces of "Air_opensurf", setting the flow direction as tangential to these would effectively hinder flow from entering through them, which would be similarly unrealistic. It will therefore be assumed that the distance between the boundary and the coil is large enough to compensate for this inaccuracy.

The temperature on this boundary (which corresponds to the free-stream or room temperature) was set at 21°C.

"Air_isolsurf" This surface is in contact with the inner surface of the coil and was defined as being adiabatic.

"Cast_Air" Interface Heat transfer was activated for this interface with no further options.

"Cast_isolsurf" The equivalent to "Air_isolsurf", but in the "Cast" domain. This surface is in reality covered by the magnet yoke, but this analysis conservatively neglects any heat

transfer between coil and yoke.

"Copper_Cast" Interface As mentioned before, the conductor coating was not included in the geometric model of the coil and consequently neither in the meshed model. However, CFX offers a method to still take this layer of different material into account, which is the *Thin Material* option for the *Heat Transfer Interface Model*. Once heat transfer is activated for a domain interface, different models can be added. The material "Polyamide imide" was chosen for the *Thin Material* option, with the thickness of 0.1 mm.

Initialisation

The initial temperature was globally set at 21°C (*Automatic with Value* option). The initial pressure and velocity components were left with the default *Automatic* option.

Solver Set-Up

The CFX option *Auto Timescale* was used both for the *Fluid* and the *Solid Timescale Control*. This function "uses an internally calculated physical time scale based on the boundary conditions, flow conditions, physics, and domain geometry" (ANSYS Inc., 2013b, p. 453). A detailed description of the time step calculation for fluids and solids can be found in ANSYS Inc. (2013c) on pp. 65–67.

An RMS residual of 10^{-4} was chosen as the convergence criterion.

3.1.4 Post-Processing

The post-processing environment of ANSYS CFX is called *CFD-Post*. This is where the results of the simulation can be visualised and manipulated. Formulas can be introduced using the *CFX Expression Language* (CEL). The following variables were retrieved from the results of every simulation: the surface temperature, the temperature at the opening, the heat transfer coefficient, the surface heat flux and the air velocity. For each variable the minimum, average and maximum values were registered. This was realised by creating a table in *CFD-Post* and using the CEL functions

minVal(<Variable|Expression>@<Location>

areaAve(<Variable|Expression>@<Location> or **volumeAve**(<Variable|Expression>@<Location>

maxVal(<Variable|Expression>@<Location>

to extract the minimum, average and maximum values.

A CFX interface has two sides and comprises in reality two different boundaries (see Table 3.6). The "Cast" side of the interface was considered the most correct one for evaluating all variables that relate to the coil surface.

Surface temperature The variable *Temperature* was read on the boundary "Cast_Air Side 1".

Opening temperature The temperature on "Air_opensurf" was monitored to check for large deviations from the set free-stream temperature of 21°C.

Heat Transfer Coefficient One of the variables automatically included in the results file is the *Wall Heat Transfer Coefficient* (henceforth designated as h_{auto}). As described by ANSYS Inc. (2013b, p. 97), it is calculated for laminar flow by rearranging

$$q_w = h (T_w - T_{nw}) , \quad (3.1)$$

with the heat flux at the wall q_w , the *Wall Temperature* T_w and the *Wall Adjacent Temperature* T_{nw} . The variable *Wall Temperature* is the "local fluid temperature at the vertex adjacent to the wall" and the *Wall Adjacent Temperature* is the "average temperature in the element adjacent to the wall" (pp. 96–97). Given that the free-stream temperature is replaced in this calculation with T_{nw} , a temperature determined close to the wall, it is to be expected that this computation will overestimate the HTC. Furthermore, *Wall Heat Transfer Coefficient* is only defined in the "Air" side of the "Cast_Air" interface. With the intention of finding a more accurate result for the HTC, two further expressions were devised to determine the HTC "manually".

The first formula simply consists of NEWTON's law of cooling with the result variables *Heat Flux* and *Temperature*. For the free-stream temperature the constant value of 21°C was inserted (in Kelvin, since *Temperature* is also solved in Kelvin). This solution of the HTC will be called h_1 . The CEL expression is:

htc1: $\text{Heat Flux}/(\text{Temperature}-294.15[\text{K}])$.

This expression was surveyed on "Cast_Air Side 1".

The second alternative expression for the HTC was derived by applying FOURIER's law to the fluid (air) on the wall and combining it with NEWTON's law of cooling. FOURIER's law can be applied at the wall surface because there the fluid velocity is zero and heat can only be transferred through conduction (BERGMAN et al., 2011, p. 380). The heat that leaves the coil, however, seen at a larger scale, is transferred through convection. So the magnitude of the conduction heat flux at the wall

$$\vec{q}_w = -k_{\text{air}} \cdot \vec{\nabla} T \Big|_{\text{wall}}$$

must be equal to the convection heat flux. This translates into the following equation:

$$-k_{\text{air}} \cdot \left| \vec{\nabla} T \Big|_{\text{wall}} \right| = |\vec{q}_w| = q = h (T_w - T_{\infty}) .$$

This equation can now be rearranged to isolate h , giving

$$h = \frac{-k_{\text{air}} \sqrt{\frac{\partial T^2}{\partial x} + \frac{\partial T^2}{\partial y} + \frac{\partial T^2}{\partial z}}}{T_w - T_{\infty}} .$$

This HTC will be denominated h_2 , and the respective CEL expression is:

htc2: $\text{Thermal Conductivity} * (\text{sqrt}(\text{Temperature.Gradient X}^2 + \text{Temperature.Gradient Y}^2 + \text{Temperature.Gradient Z}^2)) / (\text{Temperature}-294.15[\text{K}])$.

This expression was evaluated on "Cast_Air Side 2", since both the thermal conductivity and the temperature gradients must apply to the fluid side. The variable *Temperature* is thus

not evaluated on the "Cast" side of the interface, as was deemed more correct. Substituting it with an average on the "Cast" side, for instance, delivered even more unsatisfying results, so the expression was kept in this form.

Surface Heat Flux Once again information from the variable *Heat Flux* was collected on "Cast_Air Side 1".

Air Velocity A volume-weighted average of *Velocity* in the domain "Air" was performed using the aforementioned CFX function. The minimum and maximum values were also collected.

3.1.5 Sensitivity Analysis

A sensitivity analysis was performed on three parameters of the simulation, using the 1.4 A simulation as reference:

- Timescale (TS)
- Mesh Refinement (MR)
- Domain Size (DS)

Timescale

If the time step of a simulation is too large, the solver might not be able to resolve some physical effects properly. The fluid timescale was therefore decreased to half the internally calculated *Auto Timescale* value. The solid timescale was not altered since it is the behaviour of the fluid that will most determine the results of the simulation. This was achieved using the option *Physical Timescale* and inserting the value 0.0859 s (since the automatic value for both the vertical and the horizontal coil was approximately 0.1717 s).

Mesh Refinement

With the intention of keeping the coil geometry mostly intact after the meshing process, the element size in the coil domains had to be kept low and the element number respectively high. Then, to restrain the total number of elements, some mesh resolution was sacrificed in the "Air" domain. To observe the effects of this sacrifice, a finer mesh was created by decreasing the *Element Size* in "Air" to 0.005 m.

Vertical coil The resulting mesh for the vertical coil is depicted in Figure 3.5(b) on p. 29. As can be extracted from Table 3.7 in comparison with Table 3.1, all additional elements were created in the "Air" domain.

Table 3.8 further indicates a slight improvement in skewness in this domain. The minimum face angle is now in the recommended range, though the maximum element volume ratio has in turn increased slightly.

Table 3.7: Mesh information for the vertical coil (PXMCCAJWAP, MR sensitivity analysis).

Domain	Nodes	Elements	Tetrahedra	Wedges	Hexahedra
Air	309,125	1,752,717	1,752,717	0	0
Cast	618,023	2,755,200	2,755,200	0	0
Copper	247,660	171,180	0	360	170,820
All Domains	1,174,808	4,679,097	4,507,917	360	170,820

Table 3.8: Mesh quality indicators for the vertical coil (PXMCCAJWAP, MR sensitivity analysis).

Domain	Element Type	Minimum Face Angle [°]		Maximum Face Angle [°]		Maximum Edge Length Ratio		Maximum Element Volume Ratio	
Air	tetra.	15.61	(< 10)	143.92	(> 170)	3.63	(> 100)	36.61	(> 30)
Cast	tetra.	9.33	(< 10)	144.57	(> 170)	6.14	(> 100)	44.20	(> 30)
Copper	hexa., wedge	48.22	(< 10)	135.78	(–)	7.27	(> 100)	4.09	(> 5)

Horizontal coil The modified mesh for the horizontal coil is displayed in Figure 3.6(b) on p. 30. Since the global parameter *Max Size* was also altered, this time there are some new elements in the "Copper" domain, but the bulk of added elements still lies in the "Air" domain (see Table 3.9).

Table 3.9: Mesh information for the horizontal coil (PXMCCAJWAP, MR sensitivity analysis).

Domain	Nodes	Elements (Tetrahedra)
Air	303,856	1,748,399
Cast	358,127	1,540,201
Copper	350,423	1,387,152
All Domains	1,012,406	4,675,752

Table 3.10 demonstrates that the mesh quality has remained rather similar to the original mesh.

Table 3.10: Mesh quality indicators for the horizontal coil (PXMCCAJWAP, finer mesh).

Domain	Minimum Face Angle [°]		Maximum Face Angle [°]		Maximum Edge Length Ratio		Maximum Element Volume Ratio	
Air	14.95	(< 10)	148.30	(> 170)	3.74	(> 100)	48.01	(> 30)
Cast	7.67	(< 10)	143.97	(> 170)	7.11	(> 100)	39.64	(> 30)
Copper	5.59	(< 10)	145.67	(> 170)	10.17	(> 100)	28.27	(> 30)

Domain Size

To observe the effects of a larger air region, the dimensions of the box in the CAD model were doubled in every direction. The resulting model (before meshing) in the case of the horizontal coil can be seen in Figure 3.4.

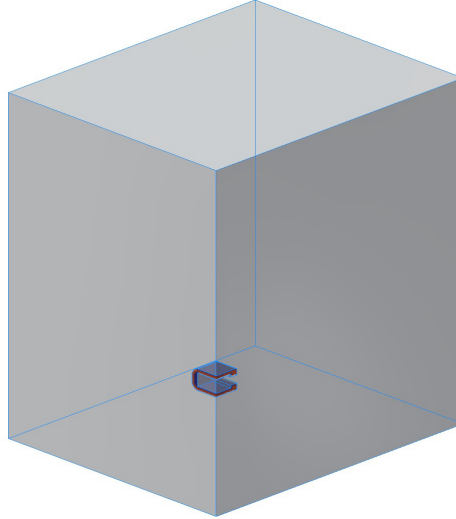


Figure 3.4: CAD model of the horizontal coil with a larger air region.

In order to keep the mesh refinement identical to the original simulation, a *Body Sizing* mesh control was applied to "Air", with the *Element Size* of 0.01 m.

Vertical coil The domain "Air" has nearly eight times the number of elements as the original mesh (see Table 3.11), which is consistent with the doubling of lengths in all three directions. The mesh is depicted in Figure 3.5(c) on p. 29.

Table 3.11: Mesh information for the vertical coil (PXMCCA JWAP, DS sensitivity analysis)

Domain	Nodes	Elements	Tetrahedra	Hexahedra
Air	303,673	1,726,359	1,726,359	0
Cast	597,935	2,668,146	2,668,146	0
Copper	241,560	165,000	0	165,000
All Domains	1,143,168	4,559,505	4,394,505	165,000

Table 3.12: Mesh quality indicators for the vertical coil (PXMCCA JWAP, DS sensitivity analysis).

Domain	Element Type	Minimum Face Angle [°]		Maximum Face Angle [°]		Maximum Edge Length Ratio		Maximum Element Volume Ratio	
Air	tetra.	6.39	(< 10)	134.91	(> 170)	8.94	(> 100)	36.19	(> 30)
Cast	tetra.	9.61	(< 10)	145.15	(> 170)	5.95	(> 100)	55.81	(> 30)
Copper	hexa.	55.58	(< 10)	135.01	(–)	3.78	(> 100)	1.35	(> 5)

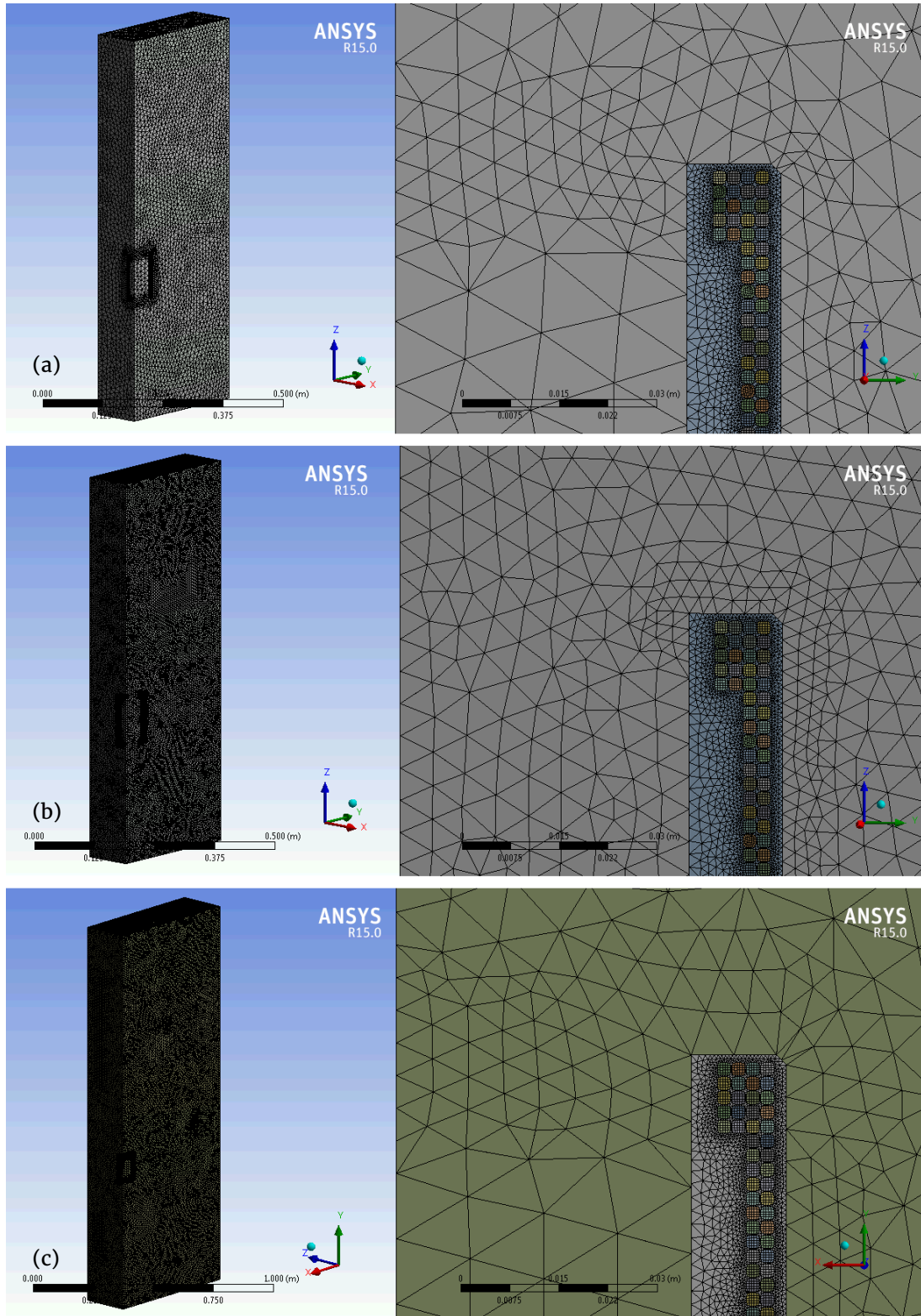


Figure 3.5: General (left) and detailed (right) views of the mesh of the vertical coil (PXMCCAJWAP). (a) Original mesh. (b) Mesh for the MR sensitivity analysis. (c) Mesh for the DS sensitivity analysis.

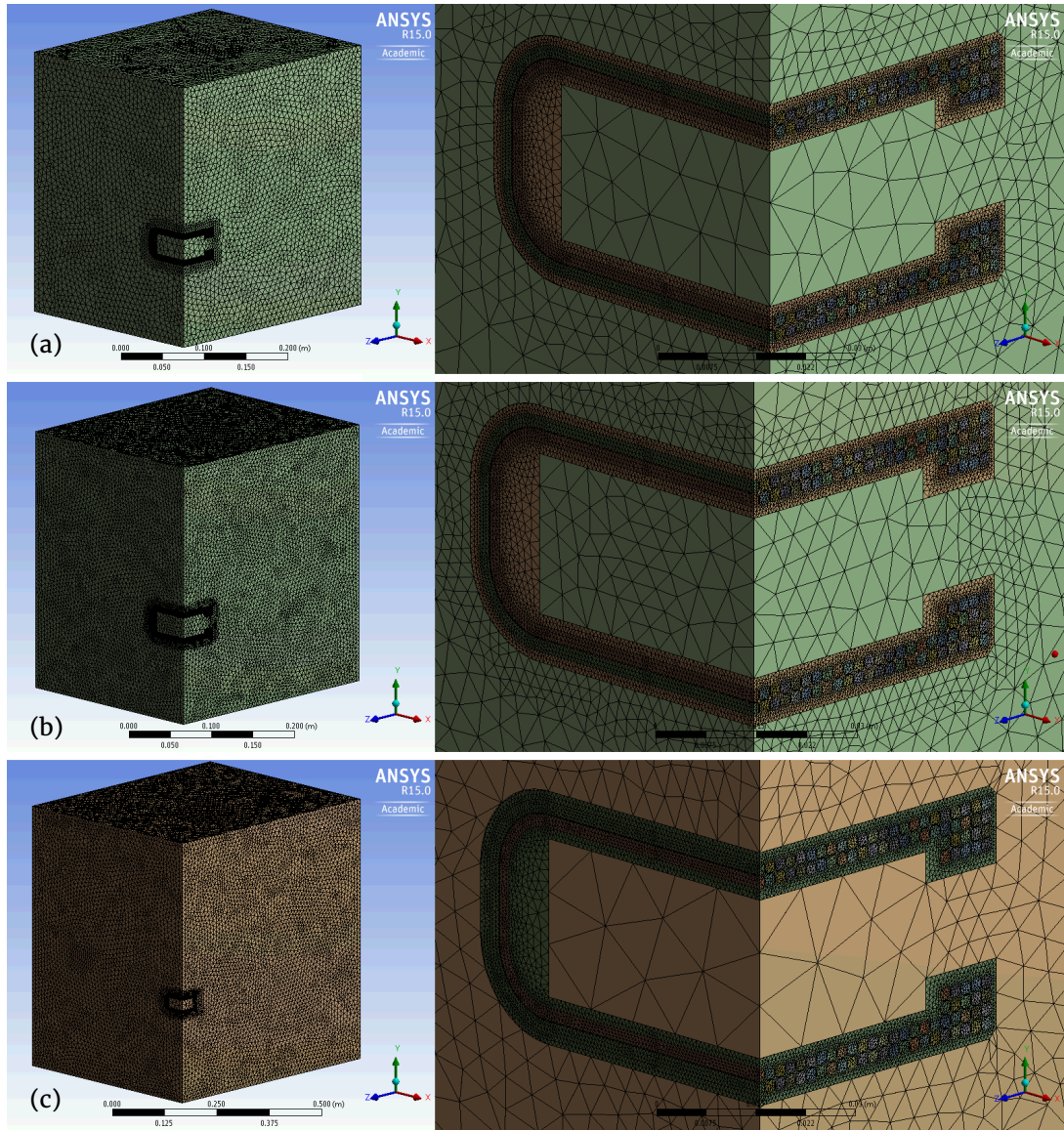


Figure 3.6: General (left) and detailed (right) views of the mesh of the horizontal coil (PXMCCAJWAP). (a) Original mesh. (b) Mesh for the MR sensitivity analysis. (c) Mesh for the DS sensitivity analysis.

Except for a few improvements in the "Copper" domain, there are no significant changes in mesh quality (see Table 3.12).

Horizontal coil In the case of the horizontal coil, the number of elements in "Air" is only a little more than six times the original number, as a comparison between Tables 3.13 and 3.3 will demonstrate.

Though the level of skewness (*Minimum Face Angle*) in the new mesh sank below the problematic threshold, the volume ratio was somewhat improved in the "Air" domain (see Table 3.14). The mesh can be seen in Figure 3.6(c).

Table 3.13: Mesh information for the horizontal coil (PXMCCAJWAP, DS sensitivity analysis)

Domain	Nodes	Elements (Tetrahedra)
Air	299,042	1,723,534
Cast	353,244	1,515,855
Copper	353,142	1,400,697
All Domains	1,005,428	4,640,086

Table 3.14: Mesh quality indicators for the horizontal coil (PXMCCAJWAP, DS sensitivity analysis).

Domain	Minimum Face Angle [°]	Maximum Face Angle [°]	Maximum Edge Length Ratio	Maximum Element Volume Ratio
Air	5.91 (< 10)	130.08 (> 170)	9.45 (> 100)	31.68 (> 30)
Cast	4.81 (< 10)	164.09 (> 170)	11.01 (> 100)	164.87 (> 30)
Copper	6.67 (< 10)	142.56 (> 170)	8.60 (> 100)	28.48 (> 30)

3.1.6 Solution

The three-dimensional character of these simulations causes a long simulation run time, which was on average close to seven hours for the ordinary simulations. The metadata for all twelve simulations is listed in Table 3.15, where the initials TS, MR and DS stand for the Timescale, Mesh Refinement and Domain Size sensitivity analyses, respectively.

Table 3.15: Solution metadata for the PXMCCAJWAP simulations.

		Number of iterations	Fluid Timescale	Total run time
Vertical coil	1.4 A	511	0.1717 s (<i>Auto T.</i>)	9 h 7 min
	TS	1000	0.0859 s (<i>Physical T.</i>)	16 h 58 min
	MR	218	0.1717 s (<i>Auto T.</i>)	5 h 33 min
	DS	583	0.2429 s (<i>Auto T.</i>)	13 h 47 min
	3.7 A	319	0.1717 s (<i>Auto T.</i>)	5 h 34 min
	6 A	214	0.1717 s (<i>Auto T.</i>)	3 h 46 min
Horizontal coil	1.4 A	460	0.1717 s (<i>Auto T.</i>)	9 h 44 min
	TS	719	0.0859 s (<i>Physical T.</i>)	14 h 33 min
	MR	201	0.1717 s (<i>Auto T.</i>)	6 h 14 min
	DS	238	0.2429 s (<i>Auto T.</i>)	6 h 58 min
	3.7 A	315	0.1717 s (<i>Auto T.</i>)	6 h 27 min
	6 A	263	0.1717 s (<i>Auto T.</i>)	5 h 39 min

It is striking that the MR sensitivity analysis requires less iterations and therefore less time than the normal simulation (in both the vertical and the horizontal case), since the mesh contains a higher number of elements. This would suggest that the original mesh is not adequate to the problem being posed, and that a finer mesh in fact offers a stabler

solution.

It is also noticeable how a more powerful heat source facilitates convergence. In both the vertical and the horizontal case the number of iterations decreases as the input current is increased, bearing in mind that no other parameter of the simulation has been changed.

The iteration number of the DS sensitivity analysis indicates different degrees of sensitivity for the vertical and the horizontal coil. The iterations remained very similar to the normal run in the vertical case, while they significantly decreased in the horizontal case (although the time step was of course different). It would therefore be expected that the DS results differ more from the 1.4 A ones for the horizontal coil, which is indeed the case, as a comparison between Tables 3.16 and 3.17 will demonstrate.

Table 3.16: Simulation results of selected variables for the vertical coil (PXMCCAJWAP).

		1.4 A	TS	MR	DS	3.7 A	6 A
T_S [°C]	min	26.53	27.37	24.21	26.27	51.77	90.14
	ave	27.39	28.44	24.84	27.41	59.12	123.53
	max	27.51	28.56	25.10	27.84	55.93	97.81
T_{opening} [°C]	min	21.00	21.00	21.00	21.00	21.00	21.00
	ave	21.00	21.00	21.00	21.00	21.01	21.02
	max	22.18	22.35	21.92	21.87	25.63	29.44
h_1 [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	1.97	2.04	1.23	1.88	2.66	2.98
	ave	4.62	4.72	4.49	4.74	5.56	5.88
	max	9.33	9.41	12.21	10.85	10.21	10.55
h_2 [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	0.44	0.45	1.11	0.54	0.56	0.57
	ave	3.15	3.19	3.66	3.27	3.51	3.64
	max	8.18	8.29	10.60	9.44	9.08	9.50
h_{auto} [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	0	0	0	0	0	0
	ave	8.98	8.90	22.55	9.06	8.29	8.08
	max	14.73	14.64	51.50	21.41	13.30	12.66
q_S [$\frac{\text{W}}{\text{m}^2}$]	min	12.75	15.32	4.99	12.65	92.04	225.91
	ave	28.14	33.25	16.85	29.49	185.25	435.52
	max	51.69	60.12	40.25	57.89	315.25	731.46
v_{air} [$\frac{\text{m}}{\text{s}}$]	min	0.002	0.002	0	0.001	0.002	0.002
	ave	0.023	0.023	0.022	0.028	0.025	0.027
	max	0.190	0.202	0.173	0.241	0.364	0.489

In all three currents the resulting surface temperature seems counter-intuitively high, reaching 120 °C with 6 A, for example. The MR simulation, however, displays more moderate values (for 1.4 A), once again suggesting that the original mesh was detrimental to the quality of the solution.

The TS analysis, on the other hand, provided even higher surface temperatures. One reason might be that the problems of the mesh are exacerbated by a smaller time step.

There was a significant difference between h_{auto} and the other HTC, especially in the horizontal case. Though the "manual" values are relatively similar, h_2 is consistently lower than h_1 , and h_{auto} consistently higher than both. Since h_2 was evaluated on the "Air" side of the "Cast_Air" interface, the variable *Temperature* that goes into its calculation should be slightly higher (the "Cast" side), which means that h_2 should in fact have even smaller values.

The change in mesh refinement greatly affected the outcome of the variable *Wall Heat Transfer Coefficient* (h_{auto}) in contrast to the "manual" HTCs, in both cases. A plausible explanation for this is that the free-stream temperature in its equation (see equation 3.1) is in fact the *Wall Adjacent Temperature*, which is an average of the mesh elements next to the wall and thus mesh-dependent. For both h_1 and h_2 , on the other hand, the free-stream temperature is kept constant. It should also be noted that the horizontal h_{auto} is roughly 60% more than the vertical result (except in the MR and DS sensitivity analyses), though h_1 and h_2 diverge little between the vertical and the horizontal case. The fact that h_{auto} remains similar in the MR and DS analyses suggests that these altered conditions result in a stabler solution, as has been deduced for the MR simulation before.

Table 3.17: Simulation results of selected variables for the horizontal coil (PXMCCAJWAP).

		1.4 A	TS	MR	DS	3.7 A	6 A
T_S [°C]	min	26.86	27.87	24.30	24.71	52.28	99.30
	ave	27.17	28.24	24.65	25.12	53.94	103.41
	max	27.41	28.52	24.88	25.37	55.19	106.39
T_{opening} [°C]	min	21.00	21.00	21.00	21.00	21.00	21.00
	ave	21.00	21.01	21.00	21.00	21.02	21.04
	max	23.10	23.43	22.37	21.84	29.82	39.46
h_1 [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	0.35	0.36	0.54	0.44	0.71	1.05
	ave	3.95	4.07	3.65	3.78	5.31	6.04
	max	10.01	10.25	11.97	13.12	12.47	13.65
h_2 [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	0.34	0.33	0.54	0.43	0.51	0.57
	ave	3.04	3.10	3.01	2.81	3.68	3.98
	max	7.29	7.35	8.06	6.75	8.06	8.39
h_{auto} [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	0	0	0	0	0	0
	ave	15.21	14.99	24.32	11.16	13.36	12.63
	max	25.04	24.51	47.50	20.21	21.60	20.95
q_S [$\frac{\text{W}}{\text{m}^2}$]	min	2.16	2.61	2.00	1.87	23.56	89.28
	ave	24.21	29.21	13.13	15.39	174.07	495.87
	max	59.56	71.44	39.79	49.45	395.80	1085.23
v_{air} [$\frac{\text{m}}{\text{s}}$]	min	0	0	0	0	0	0
	ave	0.019	0.019	0.018	0.025	0.020	0.021
	max	0.156	0.167	0.129	0.147	0.311	0.444

A comparison of the velocity vector fields in "Air" is shown in Figure 3.7 for the vertical coil (between the 1.4 A simulation and the three sensitivity analyses). It becomes at once clear that air flow close to the coil is much better resolved in the MR simulation. The boundary layer is significantly thinner than in the other simulations.

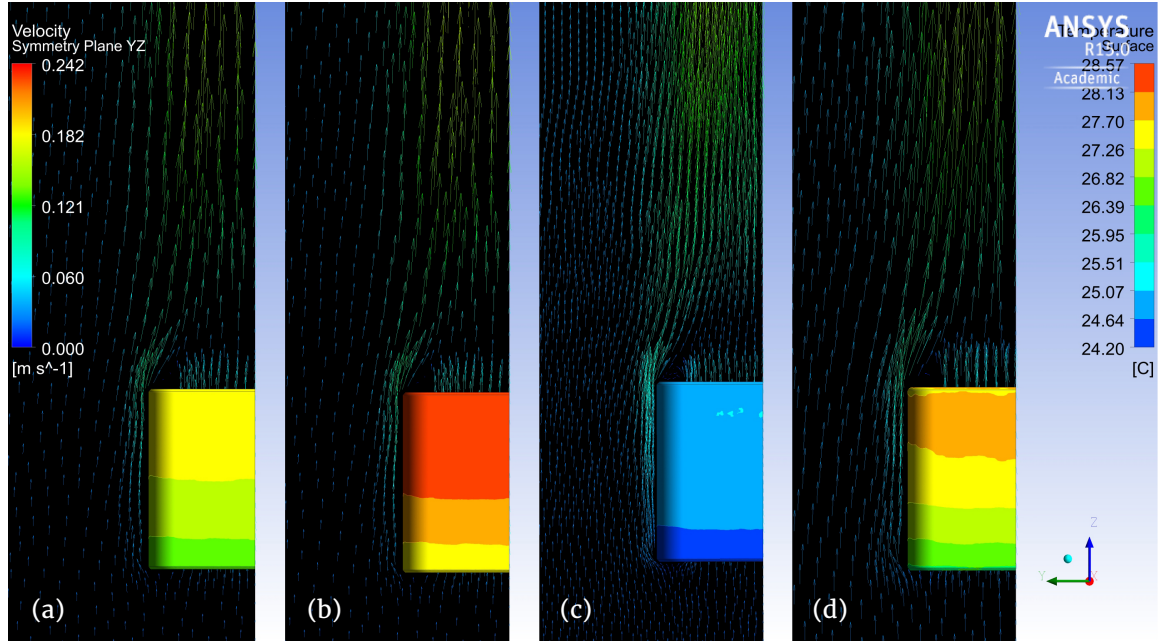


Figure 3.7: Resulting velocity vector fields on one of the symmetry planes and coil surface temperatures for the PXMCCAJWAP vertical coil for the (a) 1.4 A, (b) TS, (c) MR and (d) DS simulations.

The vector fields of the normal and TS simulations are practically identical, even though the coil surface temperature differs by about 1°C. As for the DS simulation, the main difference is a higher air velocity everywhere.

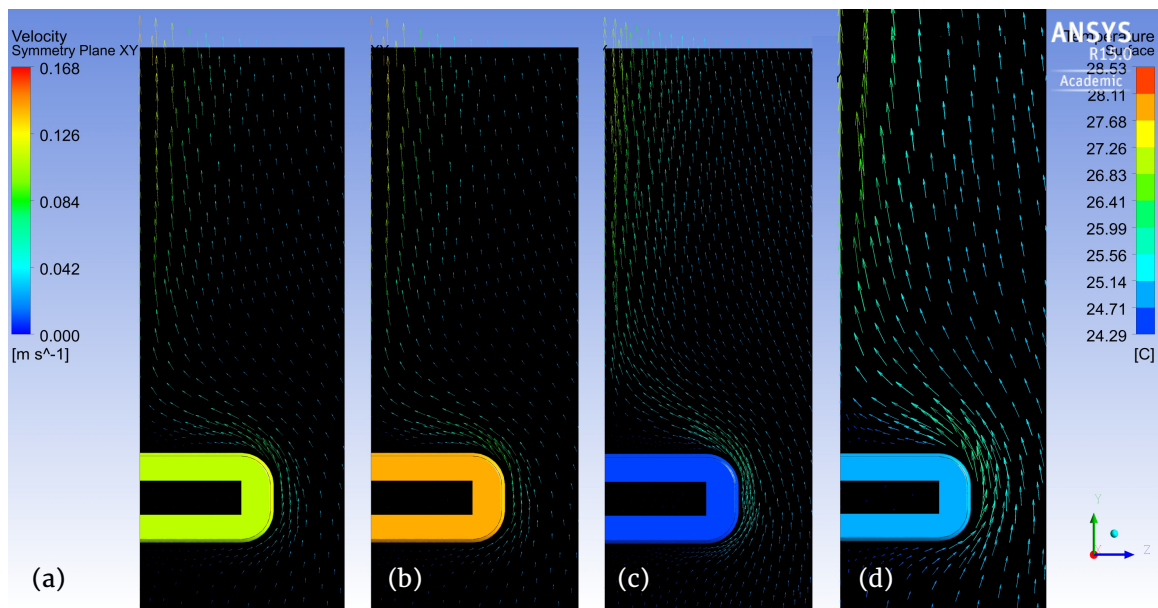


Figure 3.8: Resulting velocity vector fields on one of the symmetry planes and coil surface temperatures for the PXMCCAJWAP vertical coil for the (a) 1.4 A, (b) TS, (c) MR and (d) DS simulations.

The same aspects can be observed in the horizontal case (see Figure 3.8).

3.2 HCMCIA

A different approach was taken to simulate natural convection around the HCMCIA. The objective was to observe whether a vast simplification of the problem could still provide satisfying results in a much shorter time.

The free stream temperature will once again be set at 21°C, while the simulated RMS currents will be 3.5 A and 5.2 A. A sensitivity analysis of the same parameters as in the PXMCCAJWAP will be performed for 3.5 A (normal operation).

3.2.1 Geometric Model

As in the analytical estimation of this magnet (see section 2.2), the two coils were modelled as one single coil with double the height. The conductor inside the coil was no longer designed as individual wires and the epoxy cast around the copper no longer included in the CAD model. The CAD model therefore consists of a solid with the shape of the coil inside the air box (see Figure 3.9). Here it was only possible to use one symmetry plane, as some surfaces of one of the halves will be considered adiabatic.

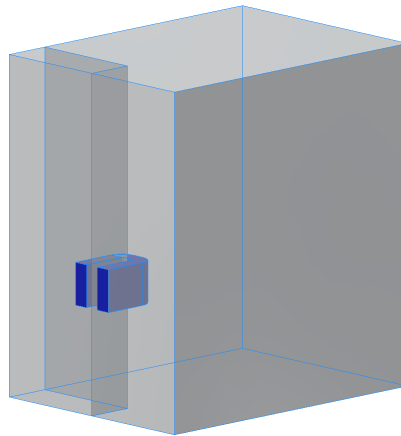


Figure 3.9: CAD model of the HCMCIA coils (including air region).

For this same reason the model had to be split in two parts. The top and bottom coil surfaces would otherwise be continuous and it would not be possible to specify only part of the surfaces as adiabatic. The CAD model then consists of four separate bodies instead of two.

Once again the dimensions of the air region were chosen according to the "chimney" configuration illustrated in Figure 3.2 on p. 18.

3.2.2 Mesh

Both bodies in the air region were meshed with tetrahedral elements. The smaller portion of the coil region (to be designated "Copper2") could be meshed using the *Sweep* method.

The other portion ("Copper1") was meshed with hexahedral elements, so as to achieve a similar mesh to the swept one. The *Element Size* was set at 0.04 m for the "Air" bodies and 0.01 m for the "Copper" bodies. All elements are quadratic elements here as well. The finished mesh is depicted in Figure 3.10, and its general information is listed in Table 3.18.

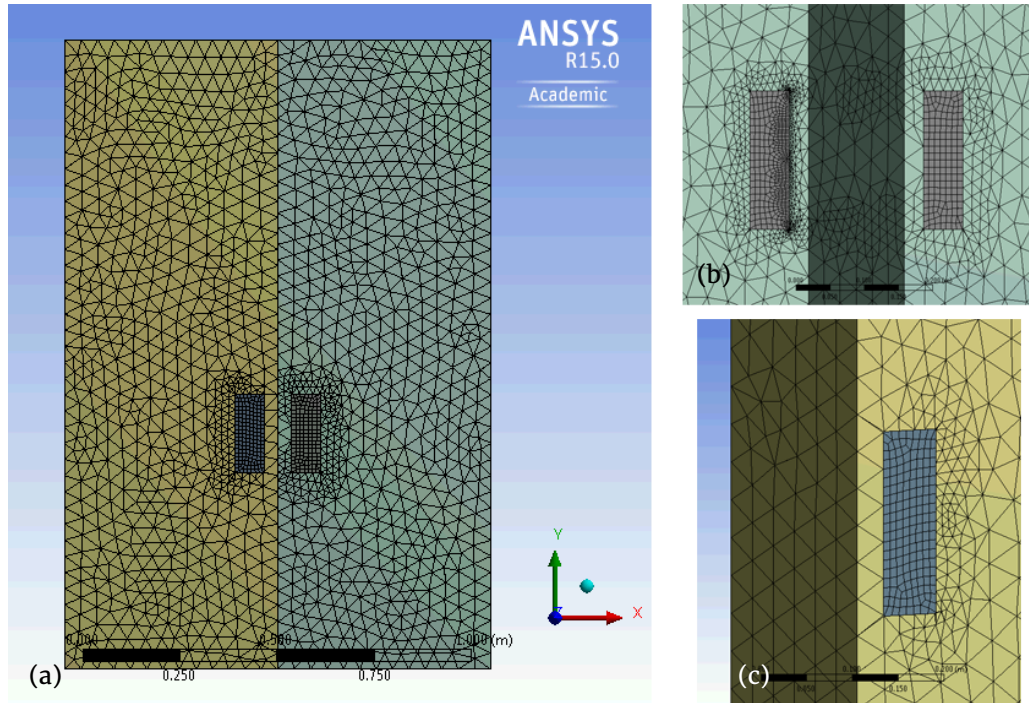


Figure 3.10: Different perspectives of the mesh (HCMCIA). (a) Front view. (b) Detailed side view of "Air1" and "Copper1". (c) Detailed side view of "Air2" and "Copper2".

Table 3.18: Mesh information (HCMCIA).

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra
Air	76,180	414,624	414,624	0	0	0
Copper	21,513	23,818	2,494	484	4,373	16,467
All Domains	97,693	438,442	417,118	484	4,373	16,467

The mesh exhibits some extreme volume ratios (see Table 3.19). This is due to some problematic areas in the model, like the inside corners of the coil seen in Figure 3.10(b) and the area between them.

3.2.3 Pre-Processing

Domains and Materials

This analysis only encompassed two domains: "Air" and "Copper". However, a layer of epoxy was included in the simulation using the *Thin Material* option.

Table 3.19: Mesh quality indicators (HCMCIA).

Domain	Element Size	Minimum Face Angle [°]	Maximum Face Angle [°]	Maximum Edge Length Ratio	Maximum Element Volume Ratio
Air	tetra.	1.16 (< 10)	152.04 (> 170)	46.26 (> 100)	313.18 (> 30)
Copper	tetra., wedge, pyramid, hexa.	2.16 (< 10)	175.15 (> 170)	17.71 (> 100)	1563.48 (> 30)

Air material The same steps were taken here as in the PXMCCAJWAP simulations (see p. 21).

Cast material The impregnating compound to be used for this magnet, according to the technical specification, is based on epoxy resin ED-16. The specification describes how many parts of each component there should be in the compound, and a paper by PETROV and PUPKOV (2011) includes in its appendix some physical properties of exactly the same impregnating compound (p. 22). The thermal conductivity and the density were adopted from this source, while the same value as before was inserted for the heat capacity, since there was no more information available.

Copper material The CFX material *Copper* was once again selected.

Table 3.20 summarises the materials and their corresponding domains.

Table 3.20: Materials used in the HCMCIA simulations and their properties, attributed to each domain.

Domain	Air	Copper	
Material	Air Ideal Gas	Copper	Epoxy
$\rho \left[\frac{\text{g}}{\text{cm}^3} \right]$	$\rho(T, P)$	8.933	1.155
$c_p \left[\frac{\text{J}}{\text{kgK}} \right]$	1006	385	1110
$\lambda \left[\frac{\text{W}}{\text{mK}} \right]$	0.0259	401	0.17
$\mu \left[\text{Pa} \cdot \text{s} \right]$	$1.83 \cdot 10^{-5}$	–	–

"Air" domain The same options were selected for the "Air" domain as in p. 22.

"Copper" domain The "Copper" domain once again acted simultaneously as the heat source. A formula for the power,

$$P(T) = I_{\text{RMS}}^2 \cdot \frac{1}{2} \cdot R_{20^\circ\text{C}} \cdot (1 + \alpha_T (T - T_{20^\circ\text{C}})) ,$$

was once again defined, with α and $R_{20^\circ\text{C}}$ (mentioned in Table 1.2) taken from the certification document. For the current the values of 3.5 A and 5.2 A were substituted. The factor 1/2 is due to the fact that half of the two coils are represented in the model (and the resistance is for both coils in series).

Boundaries and Interfaces

Since the model for the coil was split in two, an additional interface was created in each domain to connect both parts. In general the boundaries were configured with the same settings as the PXMCCAJWAP simulations (see p. 23). For the interfaces inside a domain ("Air_Air" and "Copper_Copper"), heat transfer was activated with no other options. All the boundaries are listed in Table 3.21.

Table 3.21: Boundaries and interfaces in the HCMCIA simulations.

Domain	Boundary	Type
Air	Air_opensurf	<i>Opening</i>
	Air_symsurf	<i>Symmetry Plane</i>
	Air_Air Side 1	Fluid-Fluid Interface
	Air_Air Side 2	Fluid-Fluid Interface
	Air_isolsurf	<i>Wall</i>
	Copper_Air Side 2	Fluid-Solid Interface
Copper	Copper_Air Side 1	Fluid-Solid Interface
	Copper_symsurf	<i>Symmetry Plane</i>
	Copper_Copper Side 1	Solid-Solid Interface
	Copper_Copper Side 2	Solid-Solid Interface
	Copper_isolsurf	<i>Wall</i>

"Air_isolsurf" and "Cast_isolsurf" Some surfaces of the coil were considered adiabatic: the inside of the coil and the pink surfaces in Figure 2.5 on p. 15. For this purpose these surfaces on the "Copper" and the "Air" side were defined as adiabatic *Wall* boundaries.

"Copper_Air" Interface Besides allowing heat transfer between both domains, the option "Thin Material" was activated. The selected material was "Epoxy", with a thickness of 1 mm.

Initialisation

The initial temperature was defined with *Automatic with Value* at 21°C.

Solver Set-Up

The solver was set up in exactly the same way as on p. 24.

3.2.4 Post-Processing

The same variables as in the PXMCCAJWAP simulations were surveyed and their results registered. However, all variables that apply to the coil surface were evaluated on the "Air" side of the interface, since the *Thin Material* option was activated and the "Copper" side would represent the surface under the epoxy layer.

3.2.5 Sensitivity Analysis

Once again a sensitivity analysis of the parameters Timescale (TS), Mesh Refinement (MR) and Domain Size (DS) was carried out, taking the 3.5 A simulation as comparison.

Timescale

The automatically calculated timescale was approximately 0.3746 s. For the TS sensitivity analysis, this value was halved, giving 0.1873 s. As before, this only applies to the *Fluid Timescale*.

Mesh Refinement

A finer mesh was created to observe the impact of mesh refinement on the results of the simulation. An *Element Size* of 0.02 m was chosen (for the "Air" bodies). The meshing parameters for the "Copper" bodies remained unaltered. Table 3.22 presents the element information for this mesh.

Table 3.22: Mesh information (HCMCIA, MR sensitivity analysis).

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra
Air	681,653	3,801,840	3,801,840	0	0	0
Copper	79,128	98,113	15,086	2,225	24,307	56,495
All Domains	760,781	3,899,953	3,816,926	2,225	24,307	56,495

It would be expected that a refinement of the mesh would result in a higher quality, since the elements can be better adapted to intricate geometries. This is not the case, though, as the increased volume ratios in Table 3.23 demonstrate. In fact, the finer mesh seemed to lay bare even more problematic areas (the corners of the coil, see Figure 3.11(b) on p. 40).

Table 3.23: Mesh quality indicators (HCMCIA, MR sensitivity analysis).

Domain	Element Size	Minimum Face Angle [°]	Maximum Face Angle [°]	Maximum Edge Length Ratio	Maximum Element Volume Ratio
Air	tetra.	6.35 (< 10)	156.28 (> 170)	8.47 (> 100)	536.10 (> 30)
Copper	tetra., wedge, pyramid, hexa.	2.17 (< 10)	175.25 (> 170)	15.73 (> 100)	4033.76 (> 30)

Domain Size

The size of the air region was here also doubled in every direction, to test the sensitivity of the results to it. The *Element Size* for the new mesh was kept at 0.04 m, the same as the original mesh. This resulted in the mesh statistics seen in Table 3.24. The number of

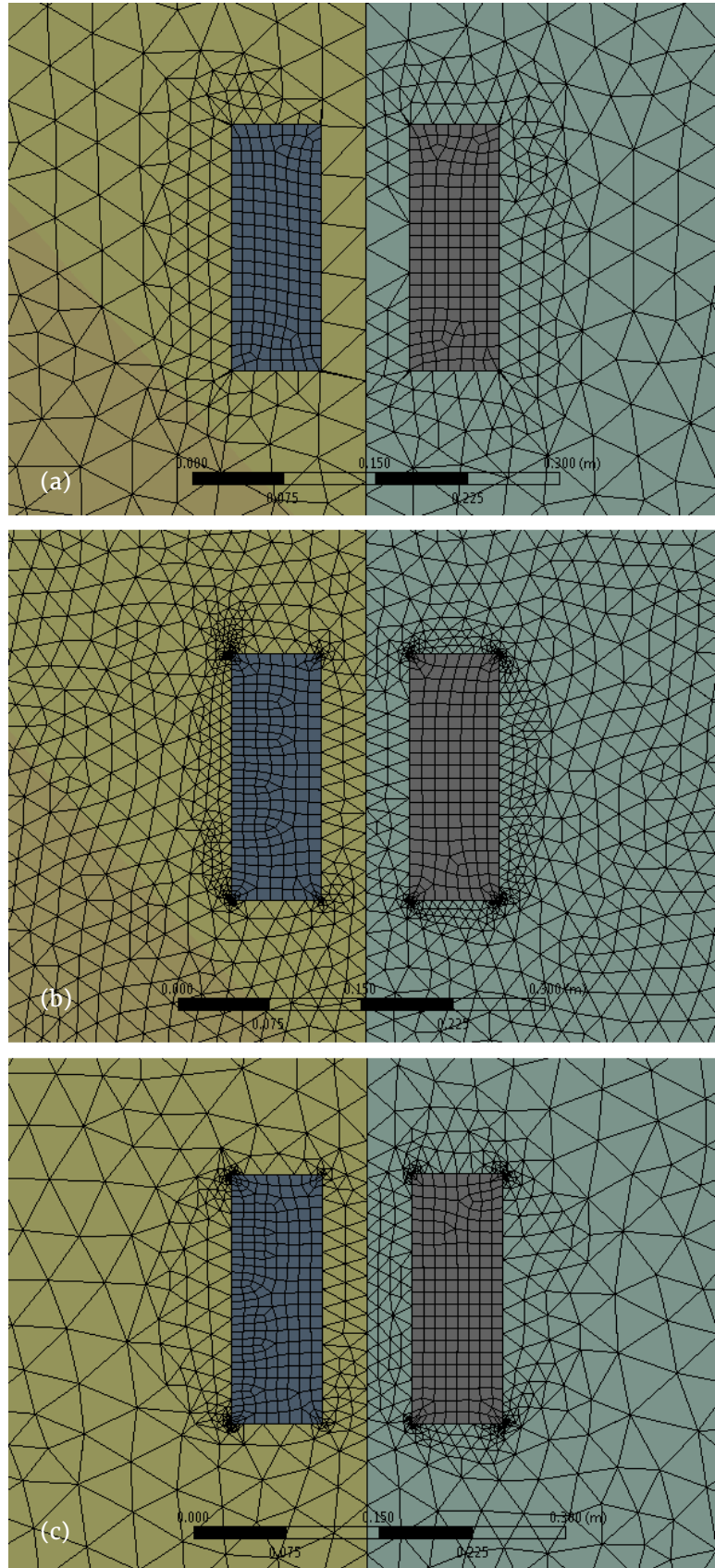


Figure 3.11: Detailed front views of the HCMCIA meshes. (a) Original mesh. (b) Mesh for the MR sensitivity analysis. (c) Mesh for the DS sensitivity analysis.

Table 3.24: Mesh information (HCMCIA, DS sensitivity analysis).

Domain	Nodes	Elements	Tetrahedra	Wedges	Pyramids	Hexahedra
Air	580,714	3,291,754	3,291,754	0	0	0
Copper	47,653	53,612	5,906	818	10,369	36,519
All Domains	628,367	3,345,366	3,297,660	818	10,369	36,519

elements in the "Air" domain is almost eight times the one of the original mesh, which is consistent with the volume increase (a factor of 2^3 , i.e. 8.).

Table 3.25 shows that the mesh quality remained roughly the same as the original mesh (Table 3.19 on p. 37). The mesh is depicted in Figure 3.11(c).

Table 3.25: Mesh quality indicators (HCMCIA, DS sensitivity analysis).

Domain	Element Size	Minimum Face Angle [°]	Maximum Face Angle [°]	Maximum Edge Length Ratio	Maximum Element Volume Ratio
Air	tetra.	7.60 (< 10)	153.75 (> 170)	7.04 (> 100)	370.59 (> 30)
Copper	tetra., wedge, pyramid, hexa.	1.96 (< 10)	171.28 (> 170)	19.04 (> 100)	1189.24 (> 30)

3.2.6 Solution

As was expected and intended, the HCMCIA simulations had a far smaller average run time, which was roughly twenty minutes for the normal simulations. This can be inferred from Table 3.26.

Table 3.26: Solution metadata for the HCMCIA simulations.

	Number of iterations	Fluid Timescale	Total run time
3.5 A	167	0.3746 s (<i>Auto T.</i>)	23 min
TS	290	0.1873 s (<i>Physical T.</i>)	41 min
MR	130	0.3746 s (<i>Auto T.</i>)	3 h 04 min
DS	108	0.5301 s (<i>Auto T.</i>)	2 h 10 min
5.2 A	157	0.3746 s (<i>Auto T.</i>)	22 min

Here some of the same observations from the PXMCCAJWAP metadata can be made. Both the MR and the DS simulations required less iterations than the 3.5 A one, even though the respective meshes have a much higher number of elements. In the case of the DS simulation, it can be argued that this is due to the larger time step. Furthermore, a more powerful heat source also resulted in faster convergence.

The simulation results for selected variables are gathered in Table 3.27. The average surface temperatures for 3.5 A are somewhat distributed, with the MR simulation delivering the highest result. The same is true for the average heat fluxes, though here it is the TS

simulation that presents the highest value. It is therefore difficult to distinguish a trend.

Regarding the three HTC variables, however, the results are always similar between the normal and the TS simulation, and between the MR and the DS simulation. The latter pair (MR and DS) displays higher values for h_2 and h_{auto} , but not for h_1 . It is in fact striking that h_{auto} differs so much from h_1 for the 3.5 A and TS simulations, but is quite similar to h_1 for the MR and DS ones (especially MR).

Another interesting fact is that the difference between the "manual" HTCs is much greater than in the PXMCCAJWAP simulations, and each method of calculation now covers a different range of values. The variable h_1 had to be evaluated on the "Air" side of the "Copper_Air" interface, the same side as h_2 and h_{auto} , which was not the case in the PXMCCAJWAP post-processing. However, this still does not explain why both formulas lead to such different values.

Table 3.27: Simulation results of selected variables for the HCMCIA coil.

		3.5 A	TS	MR	DS	5.2 A
T_S [°C]	min	21.72	22.01	23.65	23.43	22.68
	ave	33.74	38.09	45.25	41.30	47.47
	max	110.69	152.53	78.88	76.06	252.66
T_{opening} [°C]	min	21.00	21.00	21.00	21.00	21.00
	ave	21.01	21.02	21.01	21.00	21.02
	max	24.84	26.20	26.96	23.71	28.83
h_1 [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	4.63	5.22	2.07	2.28	6.11
	ave	19.34	21.82	11.43	11.55	25.78
	max	311.46	319.12	263.32	267.73	345.19
h_2 [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	0.21	0.21	0.84	0.53	0.21
	ave	1.48	1.49	2.94	2.63	1.50
	max	50.98	53.13	80.32	41.17	56.18
h_{auto} [$\frac{\text{W}}{\text{m}^2 \text{K}}$]	min	0	0	0	0	0
	ave	2.62	2.59	11.52	8.01	2.59
	max	65.34	61.86	163.85	73.85	62.02
q_S [$\frac{\text{W}}{\text{m}^2}$]	min	109.66	164.73	116.34	74.41	297.95
	ave	218.42	330.80	263.23	222.25	604.80
	max	2889.98	4413.22	2763.79	1867.18	8142.44
v_{air} [$\frac{\text{m}}{\text{s}}$]	min	0.003	0.003	0.001	0	0.003
	ave	0.035	0.036	0.035	0.038	0.037
	max	0.471	0.546	0.605	0.577	0.668

4. Measurements

In order to extract the HTC experimentally, the two magnets already discussed in this work were supplied with different currents in DC mode while the surface temperature on their coils was measured through time using thermocouples. The input voltage and current and the room temperature were also recorded through time.

It was unfeasible to let the measurements reach steady-state due to a very long stabilization period, which would have permitted using Newton's law of cooling to derive the HTC. The transient heating-up process was registered instead and a different method was devised to determine the HTC from the time-dependent temperature curves.

Set-Up

4.1.1 Devices

The devices used in the measurements of both magnets were the following:

- 16x K-type thermocouples
- National Instruments 9213, 16 channel module for thermocouple input
- National Instruments USB-9162, Hi-Speed USB carrier
- Agilent 34410A, 6.5-digit digital multimeter
- Keithley 2000, 6.5-digit digital multimeter
- National Instruments GPIB-USB-HS, GPIB controller for Hi-Speed USB
- 2x Aim-TTI PL303-P, 90W power supply
- Delta Elektronika SM30010D, 3000W power supply
- Shunt resistor 10A 75mV $\pm 1.5\%$.

4.1.2 Electrical Connection

To monitor both the current and the voltage, both multimeters were included in the circuit of the measurement. The simpler circuit, illustrated in Figure 4.1, was adopted for measurements with currents of up to 3 A, since both multimeters had a current limit with this value. One of the multimeters was connected in series with the power supply (PS) and the magnet to measure the current, while the other was connected in parallel to measure the voltage applied to the magnet. The electrodes for the voltage measurement were placed as close to the magnet input connectors as possible.

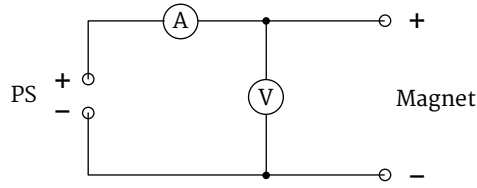


Figure 4.1: Measurement circuit for up to 3A.

A different method of registering the current was used for the higher currents. In this circuit (seen in Figure 4.2), the current was derived indirectly from the voltage drop across a shunt resistor with a known resistance (75 mV/10 A, i.e. 7.5 mΩ).

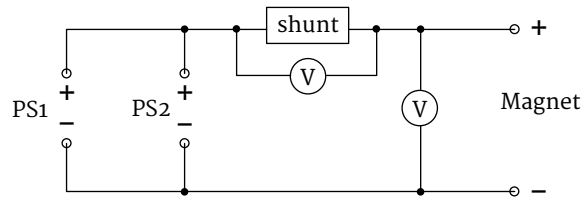


Figure 4.2: Measurement circuit for more than 3A.

The Aim-TTI power supply was also limited to 3 A, so in the case of the PXMCCAJWAP corrector, two models of this power supply were connected in parallel to deliver a higher current (see Figure 4.2). This way the supplied current could reach 6 A. In the measurement of the HCMCIA, on the other hand, a more powerful power supply was arranged for and used instead.

4.1.3 Data Connection

There were three sources of data in the measurement: the thermocouples and the two multimeters. Multiple thermocouples were placed on the magnet and their signals collected by the 9213 data module mounted on the USB carrier, which then forwards the data to a computer through a USB cable. The data from the Agilent multimeter was equally transferred from a USB output, while a GPIB-USB controller was plugged into the Keithley multimeter to convert the GPIB data format into USB.

4.1.4 Data-Logging

A data-logging environment was developed for the measurements using National Instruments's LabView software. The Virtual Instrument (VI) was created by combining different LabView tutorials and the multimeter-respective LabView drivers.

A front panel was designed where the measurement could be controlled and monitored (see Figure B.1 in Appendix B). The settings for each data source could be adjusted in "Channel Settings". For the multimeters, this meant selecting the device from a list of USB devices connected to the computer, as well as choosing the quantity to be measured and the value range, in the case of the Agilent DMM.

The thermocouple channels to be recorded could be selected from a total of sixteen available inputs. In addition, a cold junction compensation (CJC) source had to be specified. Cold junctions are the points where a thermocouple wire is connected to a device. Since the underlying principle behind thermocouples is the observed voltage between two different metals, this type of junction has the potential to corrupt the measurement. The data acquisition module used in these measurements includes an internal CJC source, so this option was chosen for all measurements.

A graph in the middle of the front panel displays the measured temperature curves for all selected thermocouple channels. On the right, two graphs show the current and the voltage from each of the multimeters. The sampling rate could also be defined in the front panel ("Timing Settings"), which was set at five seconds for all measurements. All three data sources were thus synchronised.

At the end of each iteration the readings from all three devices as well as the iteration number and the elapsed time are added to their respective array. After the measurement is completed these different arrays are passed on to the *Write To Measurement File VI* as input, appearing in the form of columns.

The VI was built in a way that channelled the values read from the different devices directly to the measurement file (see Figure B.2). For the measurements with currents higher than 3 A, the second DMM (which normally measures current) was set up to measure a voltage instead, namely the voltage drop across the shunt resistor. This value was then divided by the resistance of the shunt ($0.0075\ \Omega$) to obtain the current, before being delivered to the measurement file VI. These steps are not included in Figure B.2 though, since the necessary modifications for these measurements are minimal.

After the "Stop" button has been pressed during a measurement, a window appears and a comma-separated file generated from the *Write To Measurement File VI* can be named and saved.

4.1.5 Measured Points

PXMCCAJWAP

The chosen points for the temperature measurement are shown in Figure 4.3.

One thermocouple (in the form of a long metal rod) was reserved for the room temperature (T_0). The remaining thermocouples were mostly distributed in symmetric pairs on the coils, with the exception of the last one, which was used to monitor the surface temperature of the iron yoke (T_{15}).

HCMCIA

The same principle was applied to the HCMCIA magnet, however, two fewer thermocouples were placed. Here the thermocouple for the yoke surface temperature was T_{13} instead of T_{15} . The chosen points can be observed in Figure 4.4.

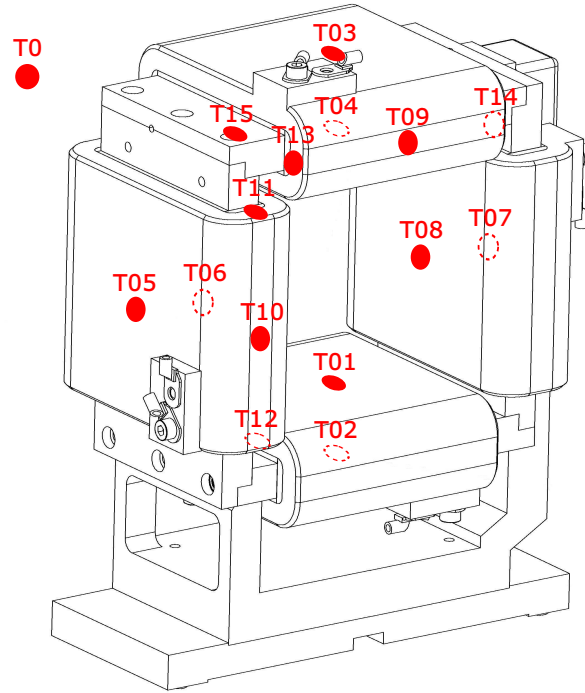


Figure 4.3: Schematic of the points where thermocouples were placed for the measurements of the PXMCCAJWAP.

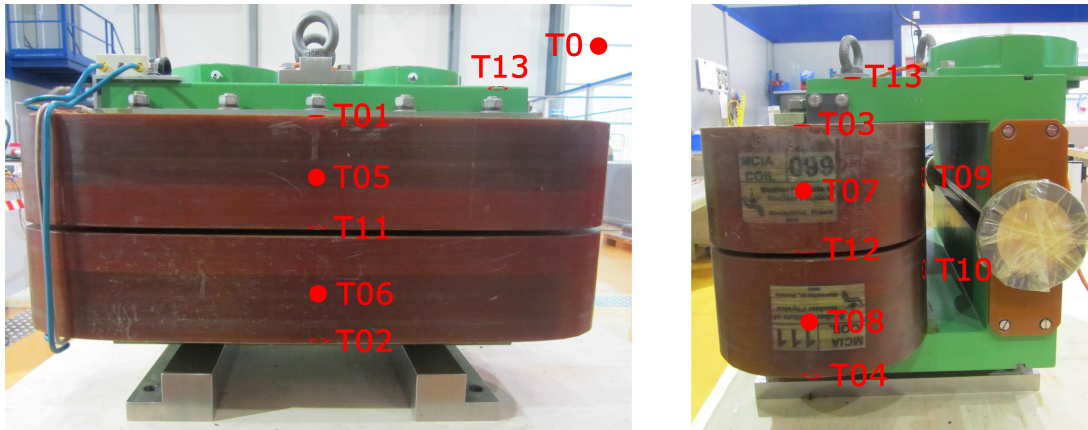


Figure 4.4: Illustration of the points where thermocouples were placed for the measurements of the HCMCIA from a front (left) and a right side view (right).

4.1.6 Final Set-Up

PXMCCAJWAP

The final set-up for the PXMCCAJWAP can be seen in the following photographs. Figures 4.5 (a) and (b) show the magnet with all thermocouples in place. In an attempt to reproduce the more constrained conditions of an accelerator beam line, where these magnets are located during normal operation, some sheets of a hard plastic-based material were positioned around the magnet to limit air flow (see Figure 4.5(c) and Figure 4.6). The thermocouple

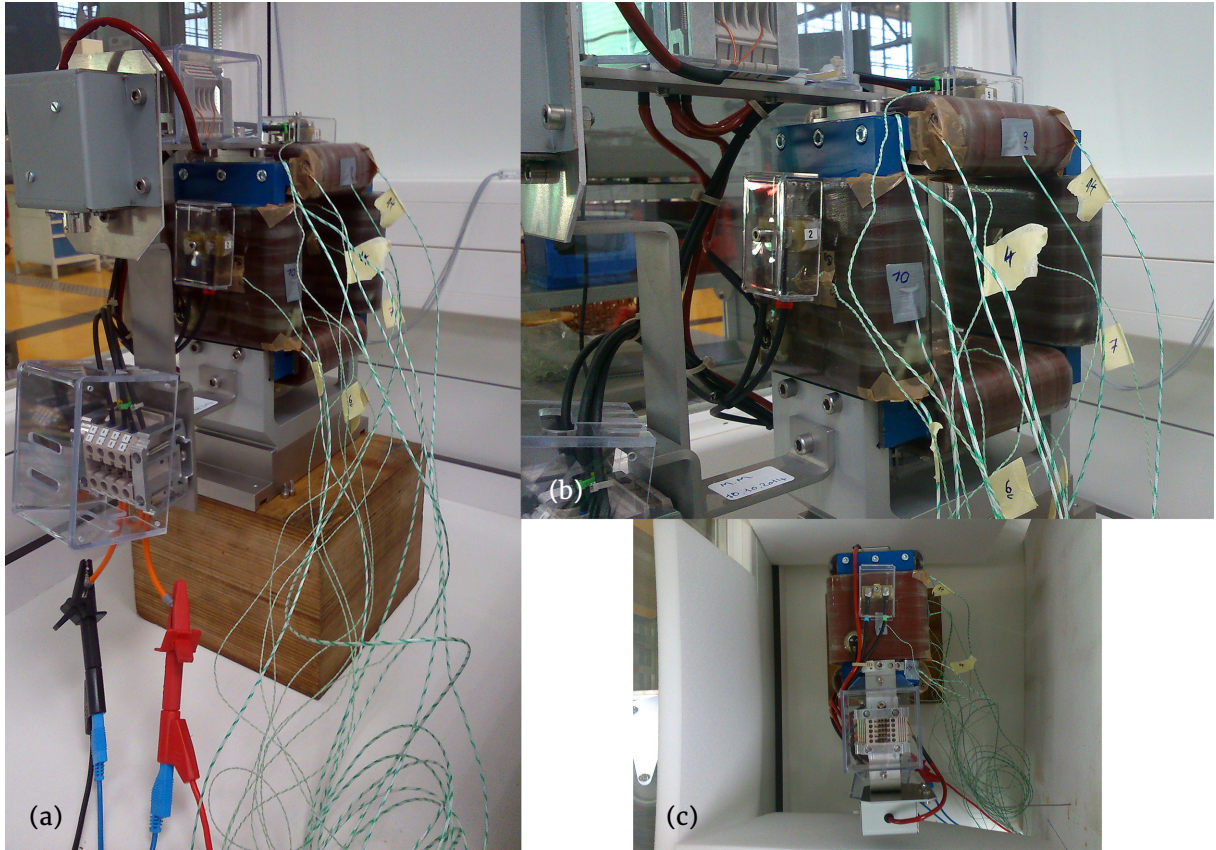


Figure 4.5: Photographs of the PXMCCAJWAP magnet ready for measurement. (a) General view. (b) Close-up view. (c) View from above with plastic sheets.

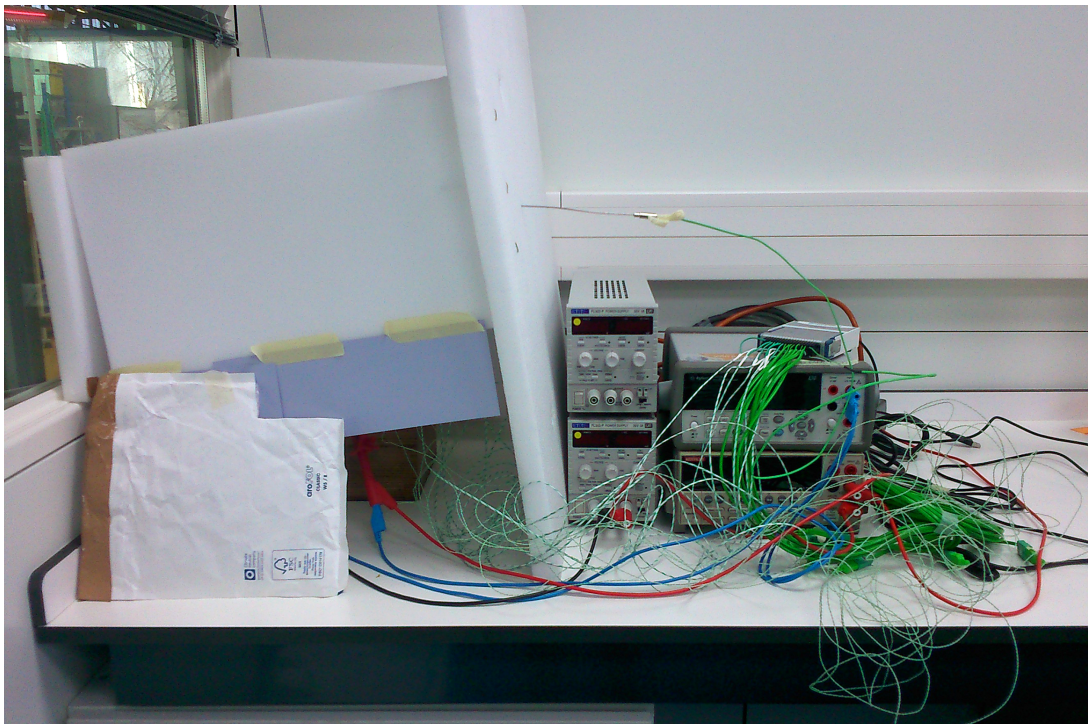


Figure 4.6: Photograph of the complete set-up for the PXMCCAJWAP magnet measurements.

rod for the measurement of the room temperature could then be inserted through the plastic sheet at a certain height (see bottom right corner of Figure 4.5(c) and centre of Figure 4.6).

Figure 4.6 shows the complete set-up (excluding the laptop computer) without the shunt resistor (for $I < 3\text{ A}$). The Aim-TTI power supplies are stacked in the middle, with the two multimeters placed to their left. The thermocouple input module mounted on the USB carrier lies on top of the multimeters.

HCMCIA

The following photographs display the shunt set-up for the HCMCIA magnet, since even the lowest current used for measurement surpassed the 3 A limit. Figures 4.7(a) and (b) show the magnet with the thermocouples in place, while the thermocouple input module features in Figure 4.5(c).

The shunt resistor can be seen in Figure 4.8 (bottom centre), alongside the Delta Elektronika power supply and the two multimeters.

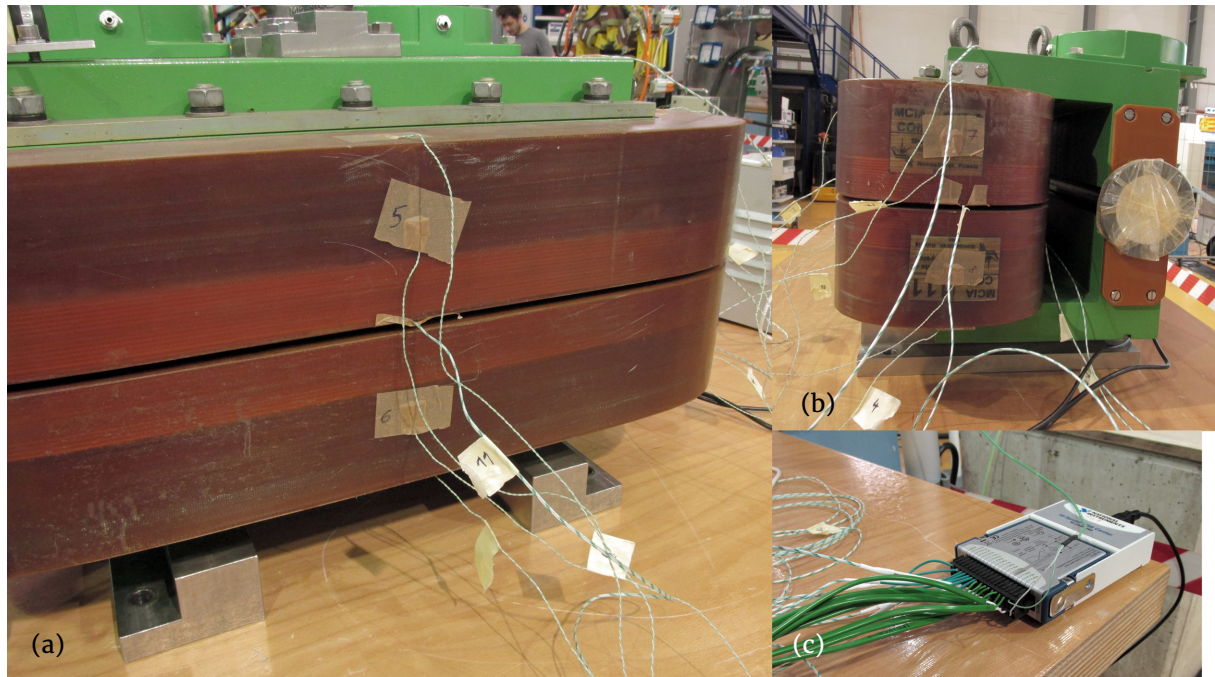


Figure 4.7: Photographs of the HCMCIA magnet ready for measurement.

Given the size and weight of the HCMCIA magnet, these measurements were conducted on a table in the middle of a large workshop area, thus rendering a confinement set-up identical to the PXMCCA/JWAP unfeasible. The thermocouple rod for the room temperature was therefore attached to a metal pole next to the table.

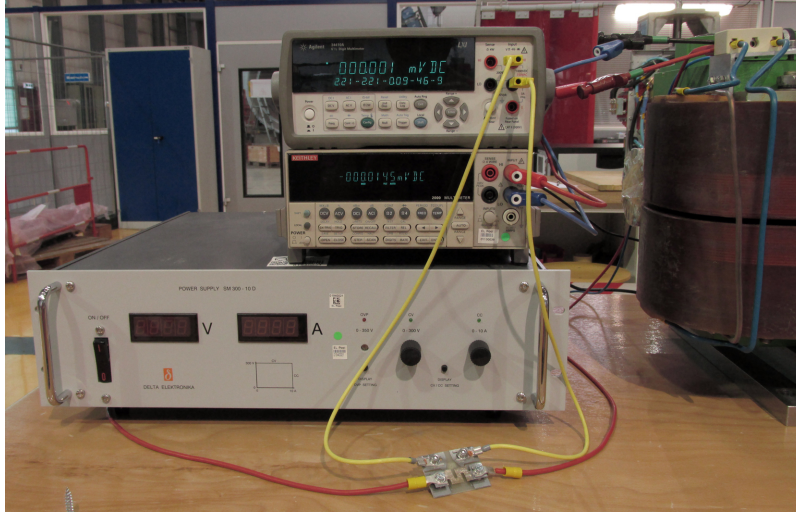


Figure 4.8: Photograph of the device set-up for the HCMCIA measurements (excluding input module and laptop computer).

Measurement Procedure

The measurements were carried out for a few selected current values, listed in Table 4.1 along with the respective current densities. The values highlighted in blue were equally used for the numerical simulations, which means that a direct comparison of the results is possible for these currents.

Table 4.1: Selected current values for the measurements of each magnet.

PXMCCAJWAP		HCMCIA	
I [A]	J [$\frac{A}{mm^2}$]	I [A]	J [$\frac{A}{mm^2}$]
1.4	0.73	3.5	0.8
1.7	0.90	4.4	1.0
2.1	1.10	5.2	1.2
2.5	1.30	6.1	1.4
2.9	1.50	7.0	1.6
3.3	1.70		
3.7	1.90		
4.0	2.10		
4.4	2.30		
4.8	2.50		
5.2	2.70		
5.6	2.90		
6.0	3.10		

Before each measurement the power supply was manually adjusted so as to provide the desired current in *constant-current* mode (this means that the current value is kept

stable while the voltage is adjusted to the changes in resistance). It was then ensured that both digital multimeters were turned on and operational. The settings in the front panel of the measurement VI were then modified to prepare it for the measurement. This implied choosing a range for the voltage measurement with the Agilent DMM (1 mV, 10 V etc.), setting the thermocouple CJC source as *Built-In* or inserting the sampling rate, for example.

After following these steps the data-logging was initiated while the power supply was simultaneously activated. After a few hours (or after the curves had begun to show signs of convergence towards an asymptote) the "Stop" button on the VI was pressed and the generated measurement file saved. The power supply was then disconnected from the circuit.

In order to accomplish two measurements in a day, a cooling fan was often positioned in front of the magnet after a measurement to accelerate its return to room temperature. The surface temperatures were monitored throughout this time until they stabilised as much as possible, at which point the fan was turned off and a new measurement was carried out.

Measured Data

4.3.1 PXMCCA JWAP

The measured temperature curves are presented on the following pages (Figures 4.9 through 4.11).

An initial remark about the room temperature must be made. The measurements of the PXMCCA JWAP magnet were conducted in a small climate-controlled laboratory room. Unfortunately, the climate control system was not working perfectly, sometimes oscillating around the set room temperature with an amplitude of around 2°C. Due to a certain time restriction, it was not possible to repeat all the measurements that were affected by this disturbance, though their number was reduced to two (2.5 A and 2.9 A). It is also clear from the temperature plots that this translated into a periodic disturbance (more so in the 2.5 A case than in the 2.9 A one), so that its influence on the final result of the data analysis can be easily and vastly minimised.

By applying a higher current to the magnet, not only an overall increase in surface temperature is observable, but also an amplification of the temperature differences between different points (compare top left graph with bottom right graph in Figure 4.10, for example). The subtler temperature changes exhibited by the measurements with lower currents also render them more susceptible to perturbations.

Though it had been expected that some pairs of symmetrical positions on the coils would register a similar temperature, like the points T05-T07, T06-T08 or T13-T14 (in Figure 4.3), this can not be observed in the measured temperature curves. One cause for this was perhaps the opening in the plastic "encasement" to the left of the magnet (see Figure 4.5(c) and Figure 4.6), thereby enabling better cooling on one side of the magnet and skewing these expected symmetries.

In fact it is impossible to find a pair or a group of curves that consistently lie next to each other throughout all the measurements, nor is there a recognisable pattern in the order

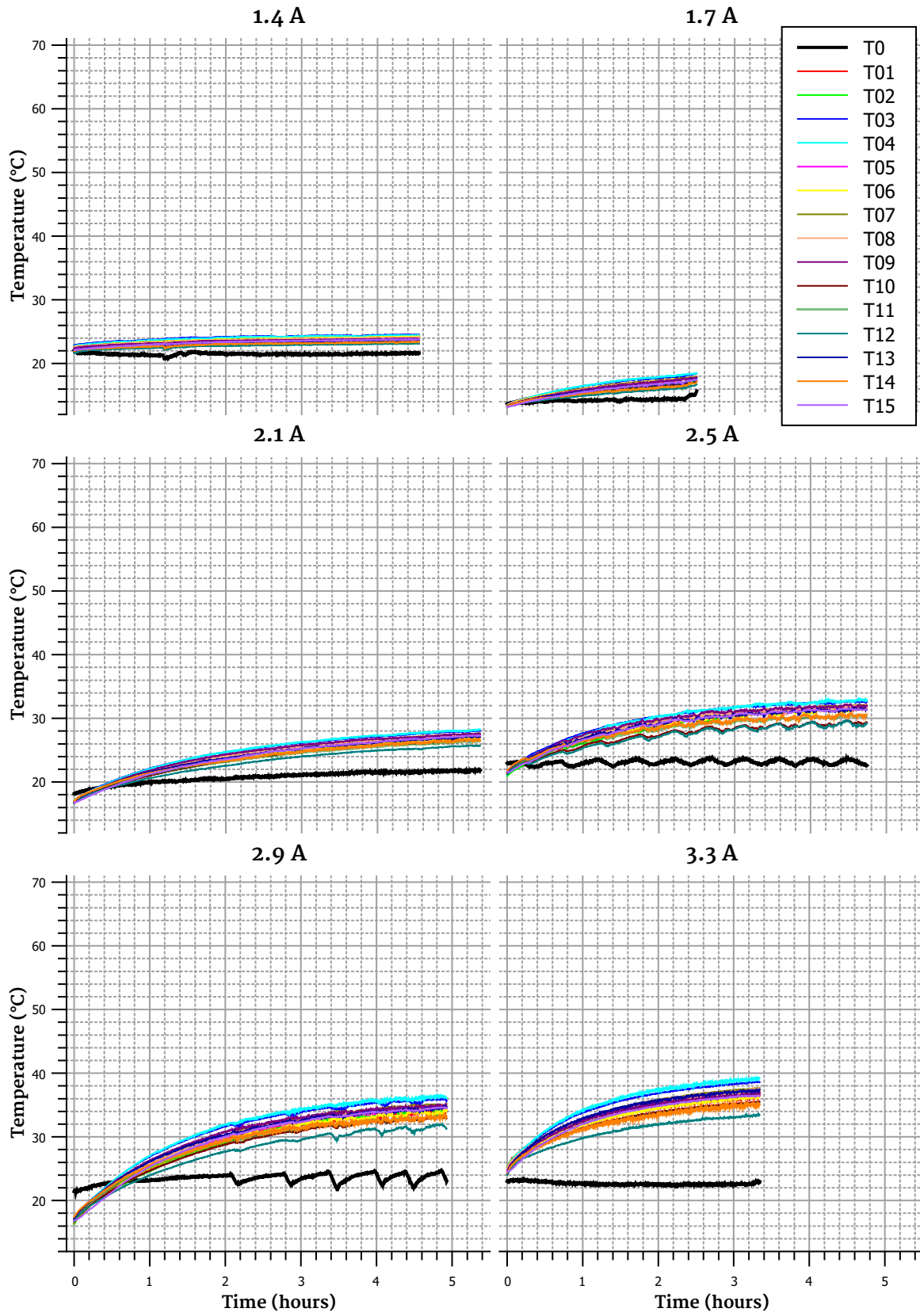


Figure 4.9: Measured temperature curves for the PXMCCAJWAP magnet (part 1).

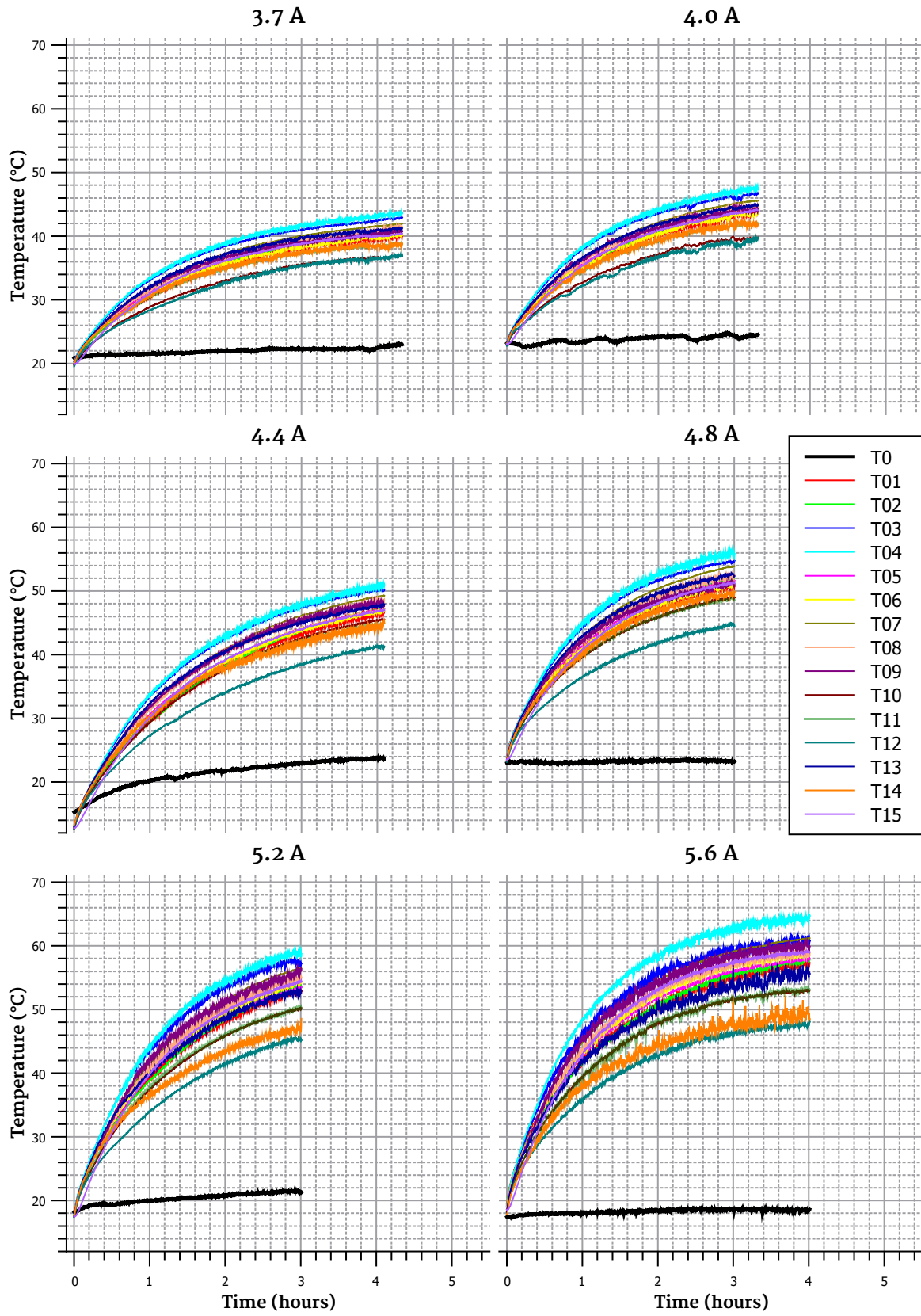


Figure 4.10: Measured temperature curves for the PXMCCAJWAP magnet (part 2).

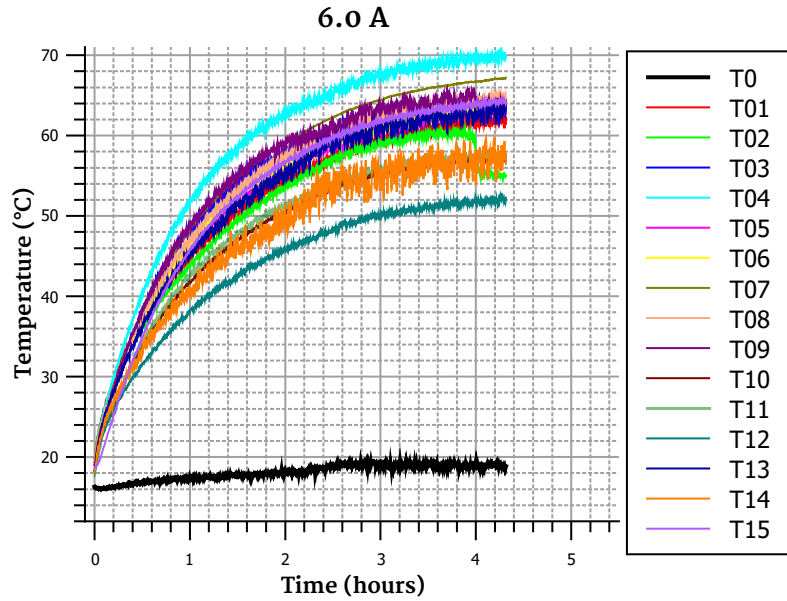


Figure 4.11: Measured temperature curves for the PXMCCAJWAP magnet (part 3).

of the temperature curves. Some identifiable pairs are only evident in a few subsequent measurements, but then appear separated in other measurements (for example curves T11 and T10 at 4.4 A through 6.0 A).

However, the locations of the highest and lowest registered temperatures, T04 and T12 respectively, are in almost perfect agreement across all measurements. For T04 the only exception is the 1.4 A measurement, which is in any case less reliable due to the subtle temperature increase. The two following or preceding curves for these extremes are also generally the same pair throughout the measurements (though in alternating order): T03 and T07 after T04, and T14 and T10 before T12.

Both T04 and T03 are located on the top coil, where heat can dissipate the most efficiently of all four coils, which also means that this is where the highest temperatures should be measured. The lower surface of the coil, however, can dissipate less heat than the upper surface, so it is to be expected that T04 registers a higher temperature than T03. T07 is the furthest point away from the opening mentioned earlier, so this might be the reason why it is constantly one of the highest temperature curves. T12, on the other hand, is closest to the opening than all other thermocouples, which makes its position at the beginning of the temperature range plausible (though it is located on a lower surface). As opposed to T10, which is also very close to the opening, point T14 evinces no obvious characteristic that could account for its position in the order of the curves.

The curve for the thermocouple placed on the magnet yoke, T15, displays a characteristic progression that makes it discernible from the other curves. At the beginning of the measurement the rate of the temperature increase is lower than that of the coil curves, but it exhibits the same behaviour as the other curves soon thereafter.

It is noticeable how the temperature curves become noisier as the current is increased. This is not true, however, for exactly three curves; T07, T10 and T15 are far less noisier than the others in all measurements.

In the graph for the 6.0 A measurement a sudden drop can be observed in curve T02 towards the end of the measurement. This was caused by the respective thermocouple becoming loose (these data points were excluded from the data analysis).

4.3.2 HCMCIA

The measured temperature curves for the HCMCIA magnet are displayed on the following page (Figure 4.12).

Once again the current increase exacerbated the temperature differences between curves besides raising the magnitude overall. The order of the curves seems to be very closely the same in all measurements, though it is difficult to identify similar pairs given the close overlap of most curves.

The two highest temperatures were measured at points T11 and T12, with some distance from the other curves. This is not surprising, since both thermocouples were placed in the small gap between the two coils, on the lower surface of the top coil, where air can only circulate with some difficulty. The lowest temperature was consistently found to be on T08 (not taking T13 into account), though with a very small difference from the bulk of the curves.

In these measurements the temperature on the magnet yoke (T13) evolved very differently from the temperatures on the coil. The yoke temperature was extremely slow to rise at the beginning, and it maintained a very large difference from the coil temperatures throughout each measurement.

Here it could once again be observed how the noise of the temperature curves became amplified towards higher currents. And here too there were a few curves with noticeably less noise than the others, namely T11 and T13 (T12 to some degree). Both here and in the PXMCCAJWAP measurements the yoke curves are included in this group, while the rest of the group represents extremes in both measurements; here T11 and T12 are the two highest curves, while the T07 and T10 curves in the PXMCCAJWAP measurements each belonged to the highest and lowest temperatures, respectively. It is nonetheless difficult to establish a cause for the lack of noise.

Data Analysis

4.4.1 Method

A method to extract the HTC for these magnets from the measured data has yet to be devised, the purpose of these measurements being its retrieval.

The initial idea was to let the magnets reach steady-state and insert the steady-state temperatures as well as the other necessary quantities in NEWTON's law of cooling to find h . The dissipated power would have been known from the product of the input voltage and current, which would have had to be dissipated in its entirety under the steady-state condition. This method, however, revealed itself to be rather time-consuming, as was mentioned earlier.

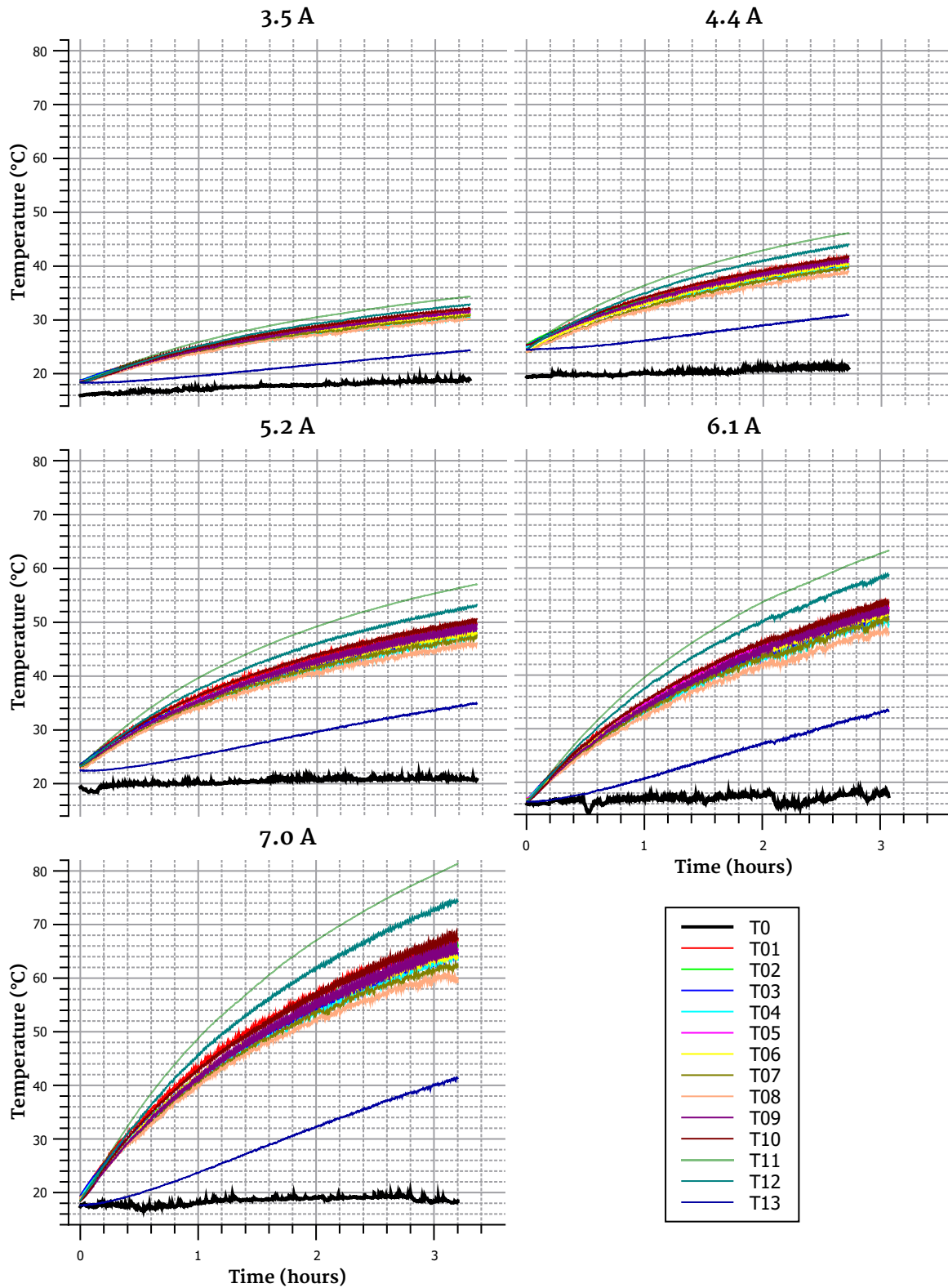


Figure 4.12: Measured temperature curves for the HCMCIA magnet.

The second idea entailed solving the transient thermodynamic problem instead and finding a mathematical description for the temperature curves. The measured curves could then be fitted to this function using h as a fitting parameter. This method will be discussed in detail in the following.

A closed thermodynamic system was defined around the coils of the magnets. In order to facilitate the derivation of the function $T(t)$, the following assumptions were made:

- $I = \text{const}$
- $R(T) = R_{20^\circ\text{C}} (1 + \alpha (T - T_{20^\circ\text{C}}))$
- $T_\infty = \text{const}$
- $c_p = \text{const}$.

Assuming a constant current is a very good approximation, since the power supplies kept it very close to the set value. The assumption of linear behaviour for the resistance of metal in this temperature range is widespread and requires no detailed explanation. The most problematic assumption is probably that of a constant room temperature. Though periodic disturbances and measurement noise can be eliminated by drawing the average over the measured data, there is often a slight overall increase throughout the measurement (see Figure 4.12 top left or Figure 4.10 centre left as an extreme case, for example). The heat capacity for the whole system was also assumed to be constant.

An equation was then established to describe changes in the system. The change in internal energy per unit time is equal to the difference between incoming and outgoing energy flows, which here correspond to the input electrical power P and convection heat flow $\dot{Q}_{\text{conv}}$, respectively:

$$\frac{dU}{dt} = P(T) - \dot{Q}_{\text{conv}}(T) . \quad (4.1)$$

According to the first law of thermodynamics, the change in internal energy is the sum of the added heat and work. No work is done on the system at hand, so dU becomes:

$$dU = dQ + dW = dQ = C_p dT = c_p m dT ,$$

where dQ was written in terms of the specific heat capacity by rearranging the definition of the heat capacity

$$C_p = \left(\frac{\partial Q}{\partial T} \right)_p = \frac{dQ}{dT} .$$

In this case Q is only a function of temperature, which means that the partial differential operator can be written as the normal differential operator. The term for dU can then be inserted in equation 4.1, along with NEWTON's law of cooling for $\dot{Q}_{\text{conv}}$.

$$\begin{aligned} c_p m \frac{dT}{dt} &= P(T) - \dot{Q}_{\text{conv}}(T) = I^2 R(T) - hA (T - T_\infty) \\ &= I^2 R_{20^\circ\text{C}} (1 + \alpha (T - T_{20^\circ\text{C}})) - hA (T - T_\infty) \\ &= T (\alpha I^2 R_{20^\circ\text{C}} - hA) + I^2 R_{20^\circ\text{C}} (1 - \alpha T_{20^\circ\text{C}}) + hA T_\infty \\ \Leftrightarrow \frac{dT}{dt} &= \frac{\alpha I^2 R_{20^\circ\text{C}} - hA}{c_p m} T + \frac{I^2 R_{20^\circ\text{C}} (1 - \alpha T_{20^\circ\text{C}}) + hA T_\infty}{c_p m} \end{aligned} \quad (4.2)$$

Equation 4.2 is a differential equation for $T(t)$ of the form:

$$\dot{T} = aT + b ,$$

i.e. a first-order inhomogeneous linear equation with constant coefficients. This type of equation can be solved using the approach $T = T_h + T_p$, where T is determined from the sum of the solution to the homogeneous problem T_h and the particular solution T_p .

The homogeneous problem is

$$\frac{dT_h}{dt} = a T_h , \quad \text{with} \quad a = \frac{\alpha I^2 R_{20^\circ\text{C}} - hA}{c_p m} .$$

Resorting to the separation of variables, the solution is found to be an exponential function with a yet unknown integration coefficient c :

$$T_h(t) = c \cdot e^{at} .$$

To find the particular solution T_p , the method of variation of parameters will be employed, by choosing $c = c(t)$. The particular solution can now be given by $T_p = c(t) \cdot T_h$. The parameter $c(t)$ can be found using the formula

$$c(t) = \int \frac{b}{T_h} dt = b \int \frac{1}{c} e^{-at} dt = -\frac{b}{ac} e^{-at} + d ,$$

where d is a further integration constant. The particular solution is therefore

$$T_p = -\frac{bc}{ac} e^{-at} e^{at} + d \cdot c \cdot e^{at} = -\frac{b}{a} + d \cdot c \cdot e^{at} ,$$

leading to the general solution T

$$T = T_h + T_p = c \cdot e^{at} + d \cdot c \cdot e^{at} - \frac{b}{a} = \tilde{c} \cdot e^{at} - \frac{b}{a} .$$

The constant $\tilde{c}$ will be determined by the initial condition, formulated as:

$$T(t=0) = T_{i,0} . \quad \Rightarrow \quad \tilde{c} - \frac{b}{a} = T_{i,0} \quad \Leftrightarrow \quad \tilde{c} = T_{i,0} + \frac{b}{a}$$

The solution to the differential equation is thus

$$T(t) = \left(T_{i,0} + \frac{b}{a} \right) e^{at} - \frac{b}{a} ,$$

$$\text{with} \quad a = \frac{I^2 R_{20^\circ\text{C}} \alpha - hA}{c_p m} \quad \text{and} \quad b = \frac{I^2 R_{20^\circ\text{C}} (1 - \alpha T_{20^\circ\text{C}}) + hA T_\infty}{c_p m} .$$

The function for T can now be used to fit the experimental data. It can be written in the form

$$T(t) = \left(T_{i,0} + \frac{I^2 R_{20^\circ\text{C}} (1 - \alpha T_{20^\circ\text{C}}) + hA T_\infty}{I^2 R_{20^\circ\text{C}} \alpha - hA} \right) \exp \left(\frac{I^2 R_{20^\circ\text{C}} \alpha - hA}{c_p m} \cdot t \right) - \frac{I^2 R_{20^\circ\text{C}} (1 - \alpha T_{20^\circ\text{C}}) + hA T_\infty}{I^2 R_{20^\circ\text{C}} \alpha - hA} . \quad (4.3)$$

In principle, all quantities in the function above are known except for h and c_p . Since both coefficients emerge in the equation coupled with another variable, hA and $c_p m$ will be treated as single variables in their stead.

The objective was to use h , or hA , as the fitting parameter for the temperature curves, so it would be convenient to remove the other unknown in the function, $c_p m$. There would thus be one less degree of freedom in the fitting process, and $c_p m$ should in any case be constant to all curves in a measurement. Once again departing from the differential equation

$$c_p m \frac{dT}{dt} = P(T) - \dot{Q}_{\text{conv}}(T) = P(T) - hA(T - T_\infty),$$

and by choosing $T = T_\infty$ (to remove the convection term from the equation), $c_p m$ could be determined using

$$c_p m = \frac{P(T_\infty)}{\left. \frac{dT}{dt} \right|_{T=T_\infty}}.$$

In practice this meant multiplying the measured voltage and current curves to obtain $P(t)$; finding the intersection of a given temperature curve with the room temperature curve; fitting the temperature curve with a general exponential function; differentiating the fit of the temperature function; finding the slope of the fit at the intersection; and finding the value for P at $t_{\text{intersection}}$. Only then could a value for $c_p m$ for one single temperature curve be found.

This already convoluted approach is further impaired by the fact that many curves do not even cross the room temperature curve. So an average drawn over all the values determined this way would be based only on part of the data, in addition to the fact that many measurements do not offer the conditions to determine one single $c_p m$ value. This approach was hence discarded.

Instead, both the variables hA and $c_p m$ were chosen as the fitting parameters. The rest of the variables in equation 4.3 will now be discussed in more detail.

- $T_{i,0}$: The initial temperature for each curve (i.e. thermocouple, i.e. measurement point) can be easily read from the measured data. The first registered value was selected and rounded to two decimal points.
- I : Since it was assumed that the current remains constant, the average of the measured values was inserted for I . This variable was therefore constant for all the curves in a measurement, but differed across measurements.
- α : The value for α could not be adopted from the certification document of the magnet because the linear approximation for $R(T)$ applies to the temperature inside a conductor and all temperatures mentioned throughout this work are surface temperatures. The input power $P(T)$ for a given measurement is furthermore exclusively dictated by the function $R(T)$ (since I is constant). $R(T)$ (and by extension the coefficient α) must therefore be specific to each measurement and describe the increase in resistance in connection with the surface temperature accurately.

For each measurement the resistance of the magnet for each point in time was derived by dividing the voltage values by the current values. The average coil surface temperature (without the room temperature and yoke thermocouples) was also determined

for every point in time, and the resistance was plotted against this average temperature. The coefficient α was then used as a fitting parameter for the resistance curve with the function $R(T) = R_{20^{\circ}\text{C}} (1 + \alpha (T - T_{20^{\circ}\text{C}}))$ (see Figure 4.13) and determined for each measurement.

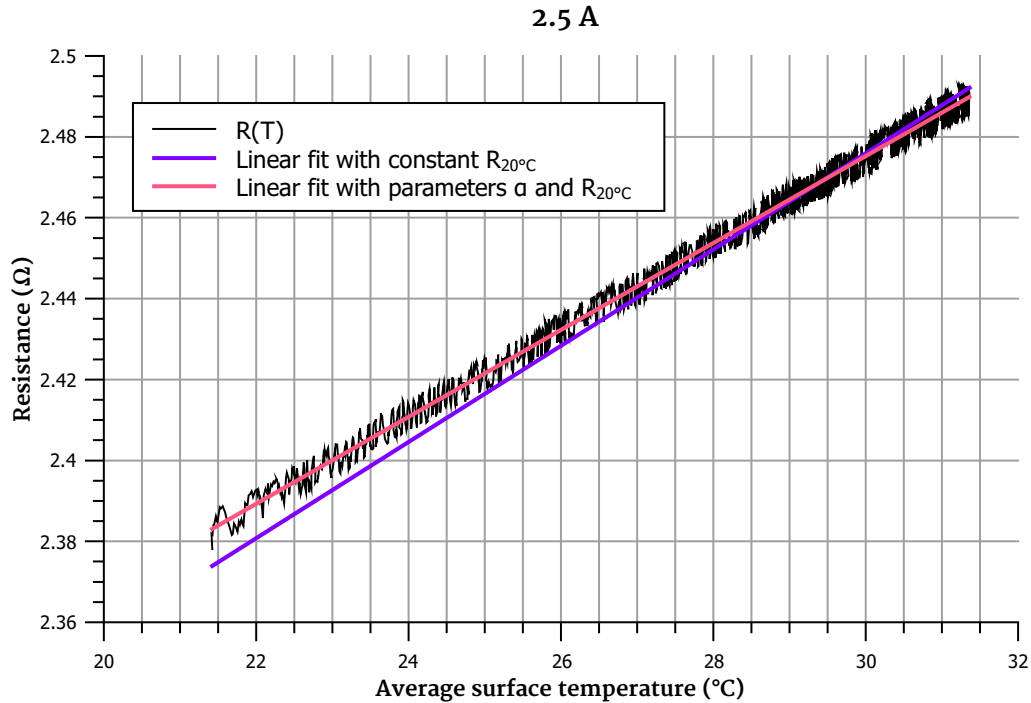


Figure 4.13: Measured resistance plotted against the average coil surface temperature for the PXMCCA JWAP at 2.5 A and two linear fits.

- $R_{20^{\circ}\text{C}}$: The initial intention was to introduce the measured resistances of each of the magnets mentioned in Tables 1.1 and 1.2 on p. 8 as a constant into the fit function $R(T)$. However, this resulted in inadequate fits, an example of which is the purple straight line in Figure 4.13. This is once again due to the fact that these resistance curves are plotted against the coil surface temperature, and not the temperature inside the conductor. Both α and $R_{20^{\circ}\text{C}}$ were therefore used as fitting parameters (the pink line in Figure 4.13 is the result of one such fit).
- $T_{20^{\circ}\text{C}}$: All temperature variables in 4.3 were given in K, so the inserted value here was 293.15 K.
- T_{∞} : The room temperature was also assumed to be constant. Analogously to the current, its value was defined as the average of T_{∞} (thermocouple T0) for one measurement.

After all these variables had been determined, the temperature curves of a measurement could finally be fitted with the function $T(t)$ (equation 4.3).

4.4.2 Results of the Analysis

Examples of the resulting fits for the PXMCCAJWAP and HCMCIA measured curves are shown in Figures 4.14 and 4.15. Only a few curves are displayed in each of the graphs, so as to allow for a better distinction between them.

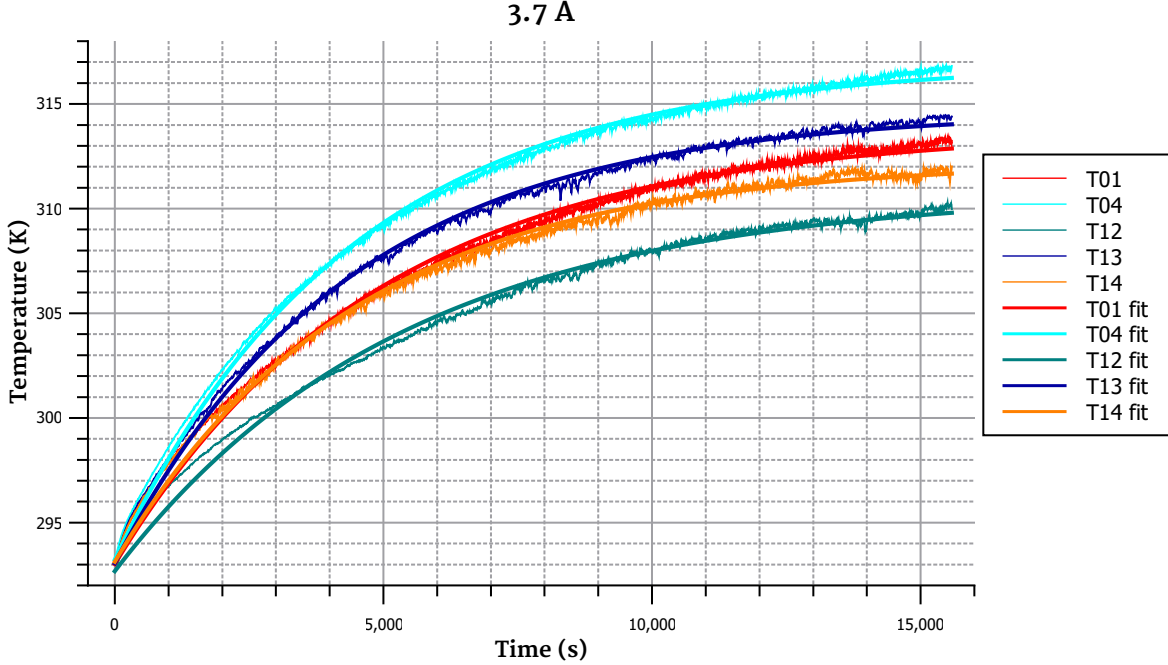


Figure 4.14: Selected temperature curves and their respective fits of the PXMCCAJWAP measurement at 3.7 A.

A clear difference in the quality of the fits can be observed in Figure 4.14 at the beginning of the graph. For T12, for example, there is a significant divergence between the measured curve and the fit, in contrast to T04. The same is true for T01 and T14. These lower-quality fits can be seen in every PXMCCAJWAP measurement, though they consistently correspond to the temperature curves that converge towards the lowest temperatures (the bottom curves in the graphs). It could thus be said that the more a temperature curve is flattened, the worse it can be described by the function $T(t)$.

This fact suggests that there might be an effect that was not accounted for in the derivation of $T(t)$ and which keeps the points concerned at a lower temperature than the rest of the thermocouples. Once again the opening in the plastic encasement of the PXMCCAJWAP set-up springs to mind as an explanation, since the added air current could be understood as a forced convection component that was not considered in the analysis of the thermodynamic system. This would also explain why only certain curves are affected.

The graphs for the HCMCIA measurements, on the other hand, do not exhibit these differences in the adequateness of the fits (see Figure 4.15, for example). This would reinforce the hypothesis that the function $T(t)$ is not fundamentally wrong, but that a difference in the set-up of both magnets caused the aforementioned anomalies (the HCMCIA magnet was not covered or protected from the environment).

The fitting procedure delivered values for the parameters hA and $c_p m$, which must now

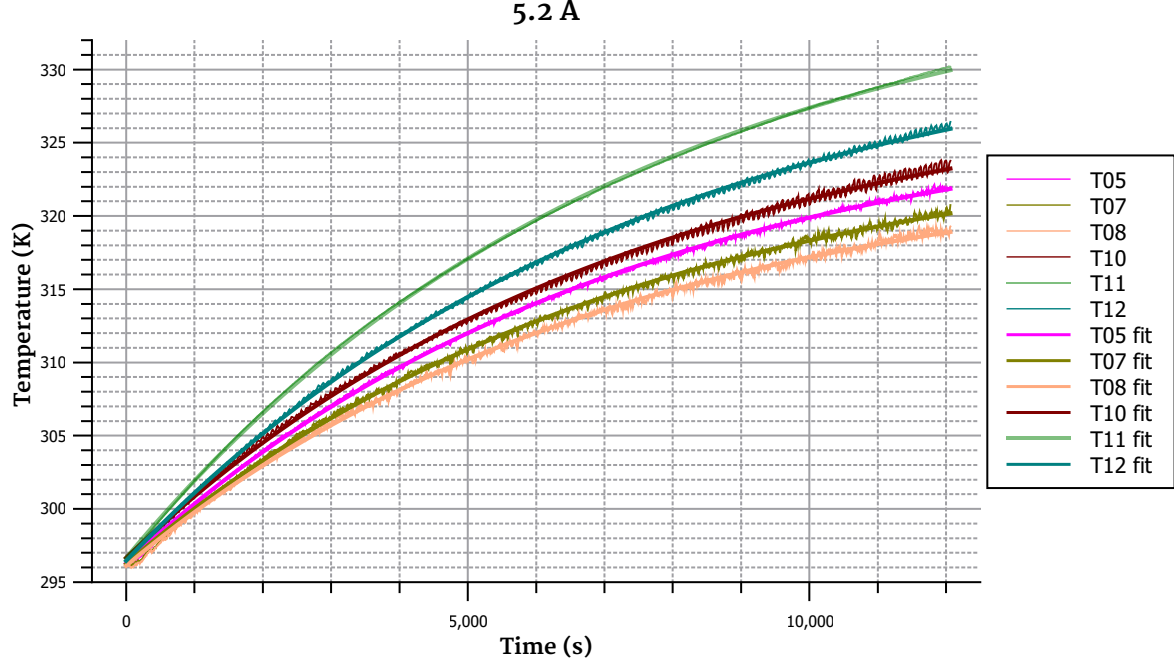


Figure 4.15: Selected temperature curves and their respective fits of the HCMCIA measurement at 5.2 A.

be evaluated.

The heat capacity $c_p m$, or C_p , as well as the specific heat capacity c_p , are of no great interest to this work. However, the resulting values for $c_p m$ should be relatively consistent for a measurement at a certain current, since c_p in reality depends on temperature.

Figures 4.16 and 4.17 display the results for $c_p m$ for the PXMCCAJWAP and HCMCIA measurements respectively, as well as the average values for each measurement (the lines in black). Neither the PXMCCAJWAP nor the HCMCIA measurements show a clear trend for C_p in relation to the current.

In the PXMCCAJWAP measurements the minimum value for $c_p m$ was on average 21% below the $c_p m$ average for that measurement, while the maximum value was on average 35% above. The HCMCIA measurements present a somewhat more consistent picture: the minimum $c_p m$ value in a measurement was on average 22% below average and the maximum value on average 12% above.

This strong variation does not seem to be linked with the temperature differences between measurement points for two reasons: on the one hand, the magnitude of the $c_p m$ deviation from the average is significantly larger than the temperature one, even for the highest currents; on the other hand, this deviation does not increase with the current, as opposed to the temperature curves, but is more or less the same for all measurements.

The fact that the heat capacity varies more than it should from a physical point of view might thus be attributable to the disturbances and experimental imperfections of the temperature curves. The parameters $c_p m$ and hA must accommodate these faults in order to enable the description of the curves with the theoretically derived function $T(t)$.

The resulting hA parameters are plotted against the currents in Figures 4.18 and 4.19 for the PXMCCAJWAP and the HCMCIA measurements respectively. The different values for hA

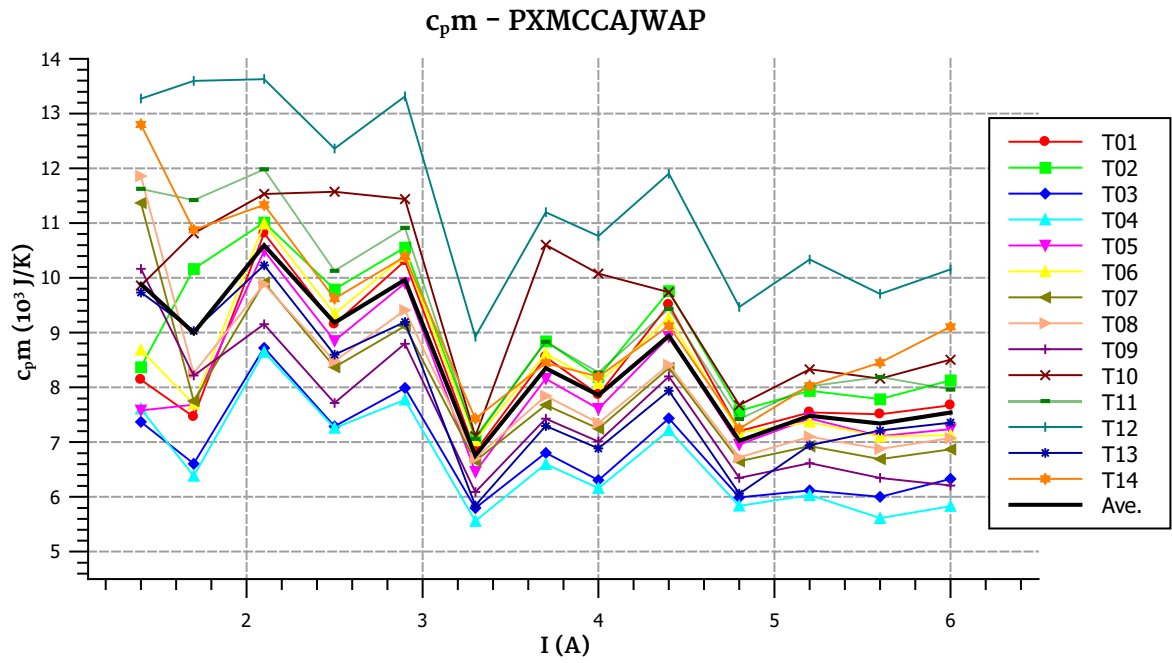


Figure 4.16: Resulting $c_p m$ values for each temperature curve plotted against the measured currents in the PXMCCA JWAP measurements.

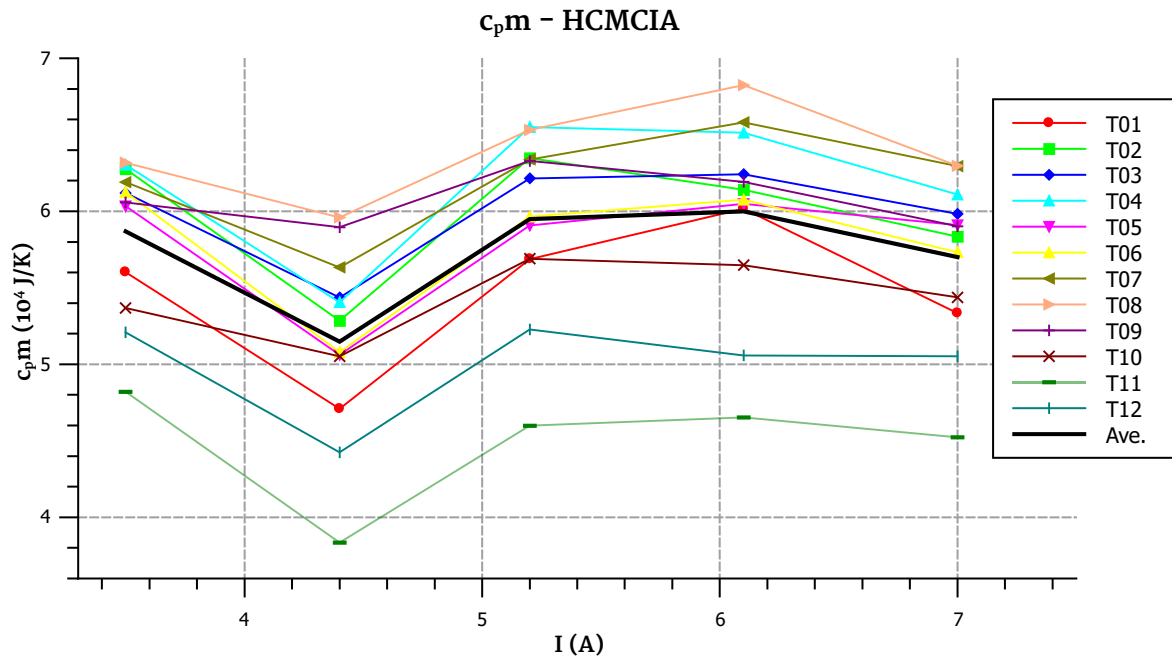


Figure 4.17: Resulting $c_p m$ values for each temperature curve plotted against the measured currents in the HCMCIA measurements.

(or h) that were found in the analysis for each curve are local (they relate to a certain point in the surface of the coil), so an average for each current must be found.

It would be incorrect to simply draw an arithmetical average over the values for all curves (as was done with the $c_p m$ data), since this would imply that the obtained HTC's are equally distributed over the entire coil surface. It is therefore more sensible to first create a curve that describes the average surface temperature over all the measured points and then fit this curve with $T(t)$ to gain the average hA . The curves named "Tave" in Figures 4.18 and 4.19 are the product of this method. It is important to stress that these curves are not the equivalent to "Ave." in the $c_p m$ plots (Figures 4.16 and 4.17).

In the graph for the HCMCIA measurements (Figure 4.19) a tendency for hA to increase with higher currents can be easily perceived. The same could be discerned in Figure 4.18 if not for the first measurement (1.4 A), which stands out from the general trend. Measurements with smaller currents are more prone to interference and disturbances, since the expected temperature increases are small and it is difficult to shield them from other effects. This may be the reason why the 1.4 A data points of the PXMCCAJWAP graph are so isolated.

It is now possible to extract the average HTC for both the PXMCCAJWAP and the HCMCIA magnets for each current, since $\bar{h}$ depends on the ratio of transferred heat flux density to temperature.

A possible course of action could be simply to divide the average hA by the free surface of the coils (the surface that is available for convective heat transfer), given that the thermodynamic system for the analysis of this problem had been defined exclusively as the coils. Pursuing this method would, however, be ignoring the share of heat flux leaving the coils that is transferred to the yoke through conduction, and which is then dissipated by the yoke through convection. This share of heat flux is far from negligible, especially in the PXMCCAJWAP case, where the temperature on the yoke surface is identical to the coil surface temperatures.

Another way to be convinced of the importance of the heat flux that is transferred to the yoke is to consider the system from a thermal resistance point of view. The system would then be a parallel circuit with two branches (yoke and coil) instead of a simple temperature potential overcoming one convective resistance. In the model the yoke branch would be a serial connection between a conductive and a convective resistance and the coil branch would consist of a convective resistance.

With the intention of compensating for the fact that the yoke was not included in the theoretical analysis of the problem, the proposed course of action is to divide hA by any surface delimited by two extremes and obtain a range of plausible HTC values.

One end of the spectrum is admitting that A is the sum of the coil free surface and the entirety of the yoke free surface. If the conductive obstacle is not too great, a system should approach this extreme as it nears steady-state. The PXMCCAJWAP magnet, for example, is very likely to be close to this extreme, since the yoke heats up at almost the same pace as the coils. In the HCMCIA case, on the other hand, the yoke seems to constitute a path with a large resistance, which may cause the largest share of heat to be transferred through the coils even in steady-state, much like the current divider in the electrical circuit analogy. The temperature curve for the yoke would then stabilise at a lower value than those of the coils as steady-state was reached, which is impossible to infer from these measurements.

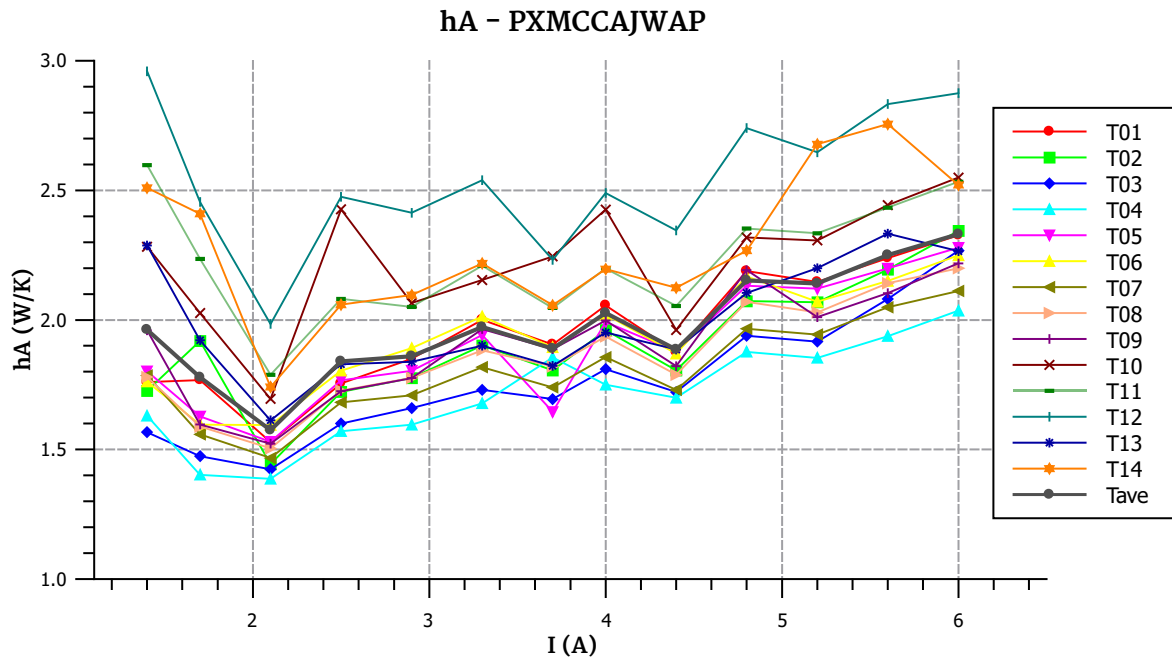


Figure 4.18: Resulting hA values for each temperature curve plotted against the measured currents in the PXMCCAJWAP measurements.

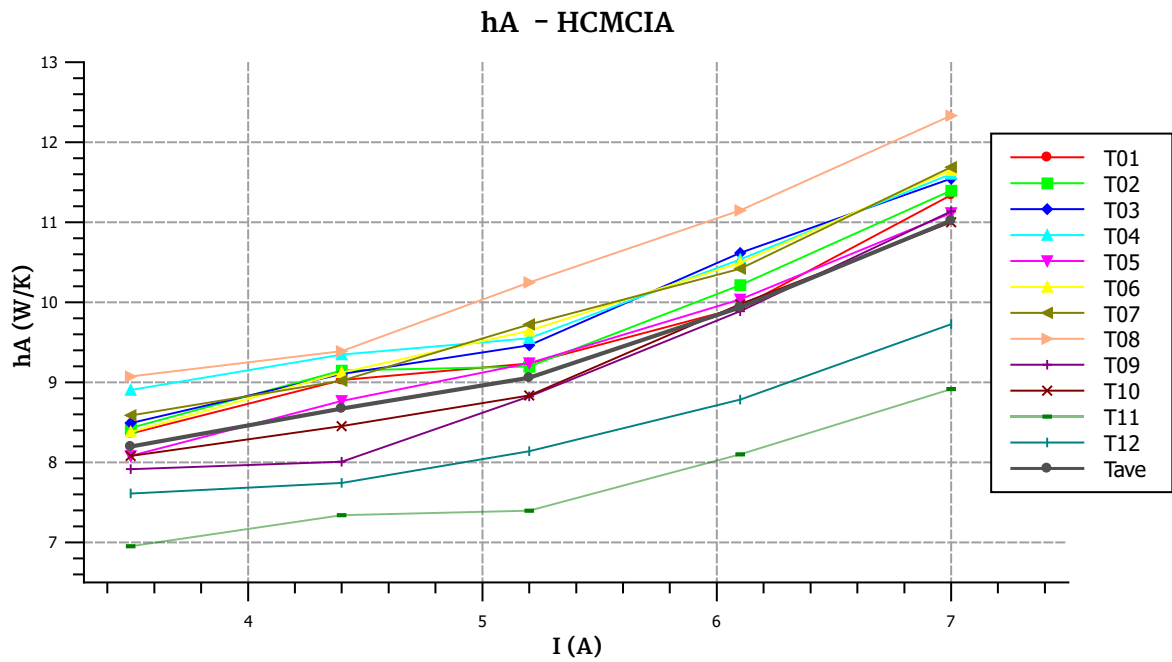


Figure 4.19: Resulting hA values for each temperature curve plotted against the measured currents in the HCMCIA measurements.

The other limit is when A corresponds solely to the coil free surface, which is unrealistic in any circumstance, as argued before.

The average HTC for each magnet can thus be placed inside a range demarcated by $0 \leq x \leq 1$, where x is the proportion of $A_{\text{free,yoke}}$ (yoke free surface) in addition to $A_{\text{free,coils}}$ (coil free surface). The coil free surfaces for each magnet are the ones that were determined for the analytical estimations (from the CAD models). The yoke free surfaces were calculated approximately, based on the technical drawings of each magnet. The values are listed in Table 4.2.

Table 4.2: Free surface values used in the calculation of $\bar{h}$.

	PXMCCAJWAP	HCMCIA
$A_{\text{free,coils}} [\text{mm}^2]$	142 167	409 651
$A_{\text{free,yoke}} [\text{mm}^2]$	24 600	618 125

The result for the average HTC is presented in Figure 4.20 for the PXMCCAJWAP magnet and in Figure 4.21 for the HCMCIA magnet on the following page.

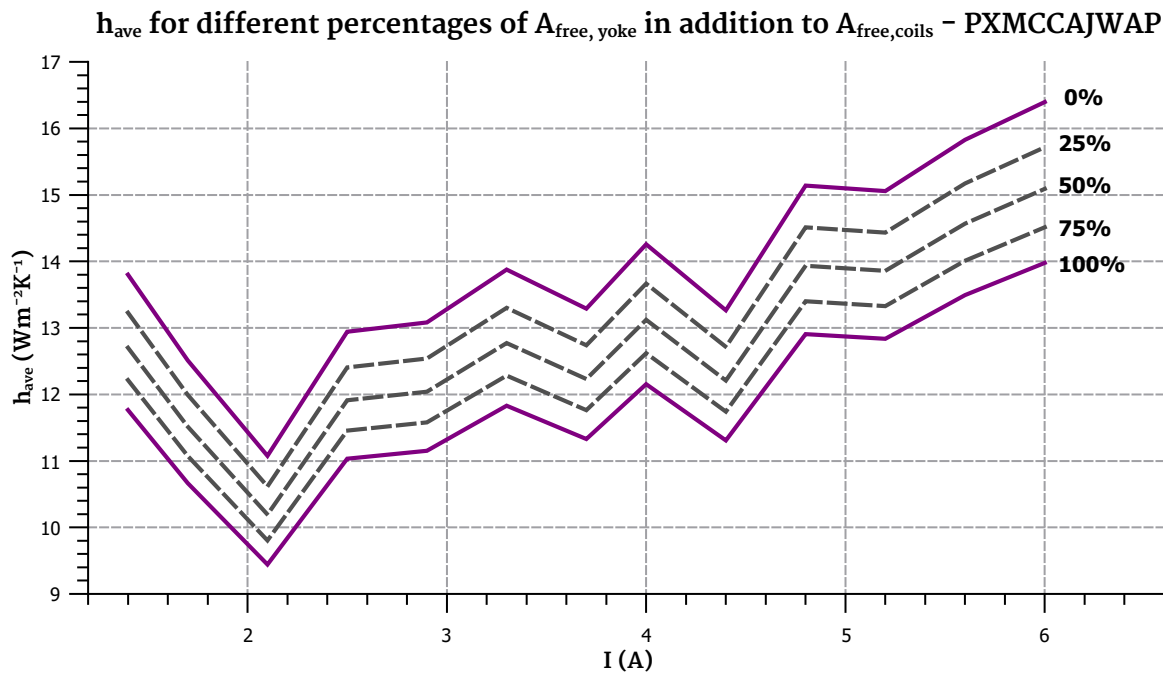


Figure 4.20: Average HTC for each current and for different portions of additional surface available for convection for the PXMCCAJWAP measurements.

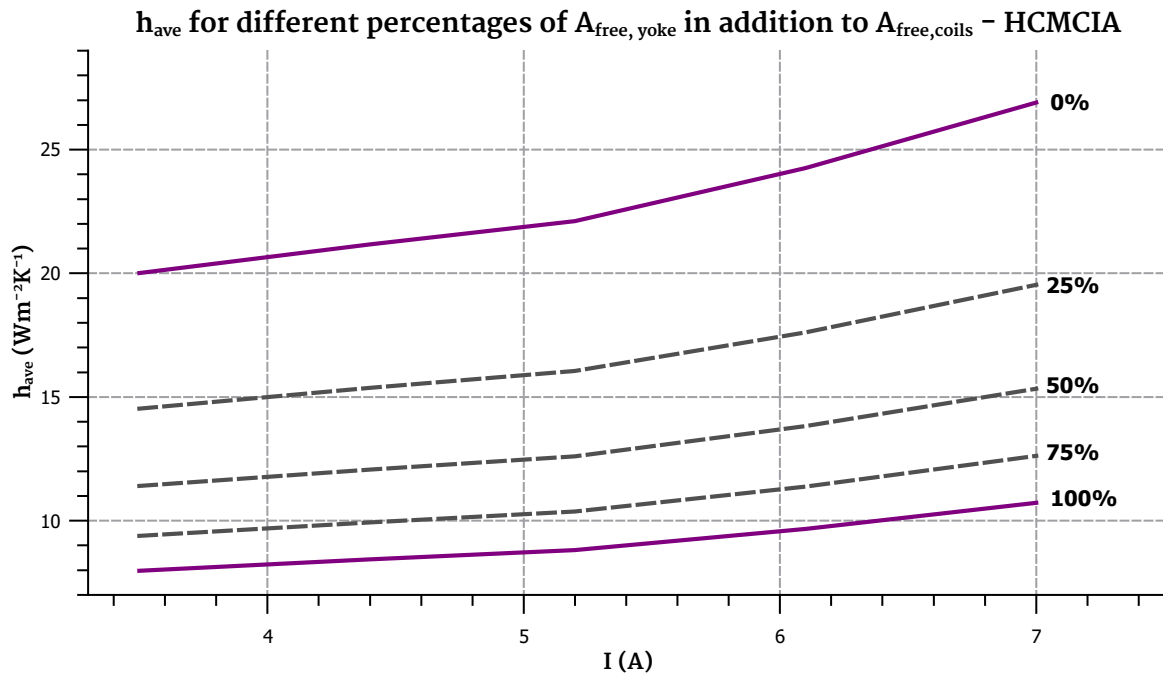


Figure 4.21: Average HTC for each current and for different portions of additional surface available for convection for the HCMCIA measurements.

5. Conclusion

In the first part of this work different methods were used to estimate the HTC for the coils of the two examined correctors, PXMCCAJWAP and HCMCIA. Later, the HTCs for the whole magnets were determined through experiments, and it was noted that the yokes of different magnets can have different contributions to the overall average HTC. A comparison between the different predictions and the experimental results is now possible, and, with it, the effectiveness of different estimation methods. Firstly, though, the results for each section must be summarised.

In the analytical estimations the average HTCs for the vertical and the horizontal coils of the PXMCCAJWAP magnet were obtained separately, so the average of both values will be used for comparison. For the HCMCIA magnet the average HTC applies to both coils.

The numerical estimations are a more complicated matter. Not only were there three different calculation methods for the HTC, but also different sensitivity analyses. However, one of the HTCs can be ruled out immediately. Although the measurements did not produce exact values for the HTC, they do clearly show that it rises with the current applied to the magnet. The exact opposite behaviour can be observed in the values for h_{auto} , which also showed a great volatility when the mesh was altered. The algorithm for h_{auto} can thus be considered unreliable and excluded from further considerations.

It was then concluded that the simulations with finer meshes delivered more correct results than the normal mesh, which is why the values for h_1 and h_2 will additionally be taken from the MR results when possible (for 1.4 A in the PXMCCAJWAP case and 3.5 A in the HCMCIA case). In the case of the PXMCCAJWAP magnet the vertical and horizontal coils were once again considered separately, so an average of both was drawn for each HTC.

As discussed before, the HTCs were gained from the measurements in the form of plausible ranges. For the PXMCCAJWAP it was argued that the real HTC in steady-state would lie very close to, or on, the 100% limit of the graph in Figure 4.20. Calculating the value exactly with 100% of $A_{\text{free,yoke}}$ for a certain current, for example, would be imprudent, however, since the results oscillate significantly around a common trend. The PXMCCAJWAP HTCs will thus be read from the graph by attempting to recognise the general trend and remain close to the 100% limit.

The steady-state HTC for the HCMCIA magnet, on the other hand, could be anywhere from around 50% to 100%, depending on the steady-state temperature the yoke reaches. The degree of uncertainty in the percentage of $A_{\text{free,yoke}}$ is nevertheless compensated by the consistency of the curve in Figure 4.21, compared with the PXMCCAJWAP curve.

The resulting HTCs for the different methods are listed in Table 5.2 for the currents that allow a comparison. With the exception of h_1 in the HCMCIA simulations, all estimations

Table 5.1: Summary of the resulting HTC's from the analytical (A) and numerical (N) estimations and from the measurements (M) (only selected currents) for both magnets.

	A [$\frac{W}{m^2 K}$]	N [$\frac{W}{m^2 K}$]		M [$\frac{W}{m^2 K}$]
		h_1	h_2	
PXMCCAJWAP				
1.4 A MR	4.38	4.07	3.34	10.5 – 11.0
1.4 A		4.29	3.10	
3.7 A	—	5.44	3.60	11.2 – 11.6
6.0 A	—	5.96	3.81	13.8 – 14.0
HCMCIA				
3.5 A MR	5.63	11.43	2.94	8.0 – 11.5
3.5 A		19.34	1.48	
5.2 A	—	25.78	1.50	8.5 – 12.5

are conservative, which had been expected. It would nonetheless be interesting to quantify the discrepancy between each method of estimation. This was achieved by dividing the difference between an estimated value and an experimental value by the latter. Since the experimental results come with error bars, the resulting relative discrepancies are also within certain ranges. They are listed in Table 5.2.

Table 5.2: Relative deviation of analytical (A) and numerical (N) estimations from experimental results for both magnets.

A [%]		N [%]	
		h_1	h_2
PXMCCAJWAP			
1.4 A MR	-58 - -60	-61 - -63	-68 - -70
1.4 A		-59 - -61	-70 - -72
3.7 A	—	-51 - -53	-68 - -69
6.0 A	—	-57 - -57	-72 - -73
HCMCIA			
3.5 A MR	-30 - -51	-43 - 1	-63 - -74
3.5 A		142 - 68	-82 - -87
5.2 A	—	203 - 106	-82 - -88

The h_1 numerical method came closest to the experimental values in one single case, namely that of the HCMCIA magnet at 3.5 A with a finer mesh. The HCMCIA simulations with the original mesh, however, result in rather extreme deviations for h_1 , thus casting some doubts on the accuracy of this method. The question remains open as to whether the simulation at 5.2 A would have yielded a similarly accurate result for h_1 as in 3.5 A MR if it had been run using the finer mesh. In that case it would have been deducible that the algorithm h_1 produces the best results when applied to a more simplistic model (with a fine mesh).

However, another fact seems to point in the opposite direction. If the MR simulations are ignored, the HCMCIA results for both h_1 and h_2 present larger deviations than

the PXMCCAJWAP ones, which would suggest that the more complex model leads to better results.

The finer mesh simulations generally resulted in a more accurate result except for h_1 in the PXMCCAJWAP case, which confirms the doubts on the reliability of this method (though the difference is relatively small).

Regarding the h_2 method, which indeed delivered more accurate results with finer meshes for both magnets, the results are overall more distanced from the measurements than h_1 . It is thus difficult to reach a decisive conclusion regarding the numerical estimation methods.

In any case, it can be said that the analytical estimations generally came closest to the measurement results (excluding the HCMCIA 3.5 A MR result for h_1), though they are quite close to h_1 in the PXMCCAJWAP case. It should furthermore be noted that these estimations were conservative by a factor of around two for both magnets, even though they are quite different. By considering the numerical results without the MR simulations, it is also visible that the estimations for the HTC rise with higher currents (i.e. more heat to be dissipated), though marginally.

The finite element method as a way to estimate the HTC should, all in all, be approached with care. There are several parameters that affect the outcome of the simulations and it can be difficult to determine which results (and which algorithms for the HTC) are the most reliable. It is besides a more laborious method than the analytical method, since the system geometry must first be modelled, which in addition becomes more complex as further system elements (like the yoke) are included and a higher accuracy is striven for.

Having obtained approximate HTCs for the PXMCCAJWAP and the HCMCIA magnets, presented methods to determine the HTC experimentally and estimate it, and having assessed these estimation methods on the basis of the experimental results, this work now comes to its conclusion.

References

- [1] ANSYS, Inc. (2013a). *ANSYS CFD-Post User's Guide*. Retrieved from <http://148.204.81.206/Ansys/150/ANSYS%20CFD-Post%20Users%20Guide.pdf>.
- [2] ANSYS, Inc. (2013b). *ANSYS CFX-Solver Modeling Guide*. Retrieved from <http://148.204.81.206/Ansys/150/ANSYS%20CFX-Solver%20Modeling%20Guide.pdf>.
- [3] ANSYS, Inc. (2013c). *ANSYS CFX-Solver Theory Guide*. Retrieved from <http://148.204.81.206/Ansys/150/ANSYS%20CFX-Solver%20Theory%20Guide.pdf>.
- [4] ANSYS, Inc. (2013d). *ANSYS Meshing User's Guide*. Retrieved from <http://148.204.81.206/Ansys/150/ANSYS%20Meshing%20Users%20Guide.pdf>.
- [5] BERGMAN, T. L., LAVINE, A. S., INCROPERA, F. P., & DEWITT, D. P. (2011). *Fundamentals of Heat and Mass Transfer*. Hoboken, NJ: John Wiley & Sons, Inc.
- [6] PETROV, V. V., & PUPKOV, Y. A. (2011). *BINP testing of radiation resistance of the materials used for production of accelerator magnetic systems*. Retrieved from http://www.inp.nsk.su/activity/preprints/files/2011_013.doc.
- [7] RICHARDSON, M. J. (2005). 2.3.6 Specific heat capacities. In *Tables of Physical & Chemical Constants*. Retrieved from http://www.kayelaby.npl.co.uk/general_physics/2_3/2_3_6.html.
- [8] Solvay Specialty Polymers Torlon® 5030 Polyamide-Imide, 30% Glass Fiber Filled (n.d.). Retrieved from <http://www.matweb.com/search/datasheet.aspx?matguid=72f466afe2634df4b6cc89ae5309fdf5>.
- [9] TOMMASINI, Davide. 2011. *Practical Definitions & Formulae for Normal Conducting Magnets*. Retrieved from CERN EDMS database (document number 1162401).
- [10] Vantico Ltd. (2000). *Araldite Casting Resin System [Brochure]*. Retrieved from <http://www.chemcenters.com/images/suppliers/169257/Araldite%20F,%20HY%20905,%20DY%20040,%20DY%20061.pdf>
- [11] Von Roll Holding Ltd. (n.d.). *Winding Wires and Litz Wires [Brochure]*. Retrieved from http://www.vonroll.ch/media/files/downloads/broschures/Wire_EN_20120516.pdf.
- [12] Wolfram Alpha LLC. (2015a). *Wolfram|Alpha*. Retrieved March 4 2015 from <http://www.wolframalpha.com/input/?i=air+dynamic+viscosity+at+21+deg+c>.
- [13] Wolfram Alpha LLC. (2015b). *Wolfram|Alpha*. Retrieved March 4 2015 from <http://www.wolframalpha.com/input/?i=air+kinematic+viscosity+at+23.5+deg+c>.

- [14] Wolfram Alpha LLC. (2015c). *Wolfram|Alpha*. Retrieved March 6 2015 from <http://www.wolframalpha.com/input/?i=air+kinematic+viscosity+at+46+deg+c>.
- [15] Wolfram Alpha LLC. (2015d). *Wolfram|Alpha*. Retrieved March 4 2015 from <http://www.wolframalpha.com/input/?i=air+properties+at+21+deg+c>.
- [16] Wolfram Alpha LLC. (2015e). *Wolfram|Alpha*. Retrieved March 4 2015 from <http://www.wolframalpha.com/input/?i=air+properties+at+23.5+deg+c>.
- [17] Wolfram Alpha LLC. (2015f). *Wolfram|Alpha*. Retrieved March 6 2015 from <http://www.wolframalpha.com/input/?i=air+properties+at+46+deg+c>.
- [18] Wolfram Alpha LLC. (2015g). *Wolfram|Alpha*. Retrieved March 4 2015 from <http://www.wolframalpha.com/input/?i=air+thermal+conductivity+at+21+deg+c>.
- [19] Wolfram Alpha LLC. (2015h). *Wolfram|Alpha*. Retrieved March 4 2015 from <http://www.wolframalpha.com/input/?i=air+thermal+conductivity+at+23.5+deg+c>.
- [20] Wolfram Alpha LLC. (2015i). *Wolfram|Alpha*. Retrieved March 6 2015 from <http://www.wolframalpha.com/input/?i=air+thermal+conductivity+at+46+deg+c&lk=4&num=1>.
- [21] Wolfram Alpha LLC. (2015j). *Wolfram|Alpha*. Retrieved March 4 2015 from <http://www.wolframalpha.com/input/?i=polyamide-imide>.
- [22] ZICKLER, T. (2010). *Basic design and engineering of normal-conducting, iron-dominated electromagnets*. doi:10.5170/CERN-2010-004.65

A Appendix

Matlab codes for the iterative calculation of the HTC

A.1 PXMCCAJWAP

Vertical coils

```
function res=PXMCCAJWAP_vert_htc()

Tinf = 294.15; %21 degrees C

k = 0.0261;
rho = 1.19;
cp = 1006;
nu = 1.524*10^(-5);
alpha = k/(rho*cp);
Pr = nu/alpha;
g = 9.81;
L = 0.101;

Pdiss = 1.177;
Afree = 0.035542;

htc = 3.7; %from first calculation
i = 1;
diff = 5;

while diff>0.0000001

    dT = Pdiss/(Afree*htc);

    Tf = (dT+2*Tinf)/2;
    beta = 1/Tf;
    Ra = g*beta*dT*L^3/(nu*alpha);
    Nu = 0.68+0.67*Ra^(1/4)/((1+(0.492/Pr)^(9/16))^(4/9));
    htcnew = k*Nu/L;

    diff = abs(htcnew-HTC);

    x(i) = i;
    h(i) = htc;
    dTv(i) = dT;

    subplot(2,1,1)
    plot(x,h)
    hold on
    title('HTC')
    xlabel('Iterations')
    ylabel('HTC')
    subplot(2,1,2)
    plot(x,dTv)
    hold on
    title('deltaT')
```

```

    xlabel('Iterations')
    ylabel('deltaT')

    htc = htcnew;
    i = i+1;
end

res = [htc, dT];

end

```

Horizontal coils

```

function res=PMCCAJWAP_hor_htc()

Tinf = 294.15; %21 degrees C

k = 0.0261;
rho = 1.19;
cp = 1006;
nu = 1.524*10^(-5);
alpha = k/(rho*cp);
Pr = nu/alpha;
g = 9.81;
L = 0.0212;
As = 0.011052;
P = 0.2836;
Lm = As/P;

Pdiss = 1.133;
Afreea = As;
Afreeb = As;
Afreec = 0.0066202;
Afreeav = Afreea + Afreeb + Afreec;
Afree = 0.035542;

htc = 4.75; %from first calculation
i = 1;
diff = 5;

% a) upper surface of hot plate
% b) lower surface of hot plate
% c) vertical plate
% no suffix: weighted average
while diff>0.0000001

    dT = Pdiss/(Afree*htc);

    Tf = (dT+2*Tinf)/2;
    beta = 1/Tf;

    Raab = g*beta*dT*Lm^3/(nu*alpha);
    Rac = g*beta*dT*L^3/(nu*alpha);

```

```

Nua = 0.54*Raab^(1/4);
Nub = 0.52*Raab^(1/5);
Nuc = 0.68+0.67*Rac^(1/4)/((1+(0.492/Pr)^(9/16))^(4/9));

htca = k*Nua/Lm;
htcb = k*Nub/Lm;
htcc = k*Nuc/L;

%weighted average (in respect to free surface)
htcnew = (Afreea*htca+Afreeb*htcb+Afreec*htcc)/Afreeav;

diff = abs(htcnew-htc);

x(i) = i;
h(i) = htc;
dTv(i) = dT;
ha(i) = htca;
hb(i) = htcb;
hc(i) = htcc;

htc = htcnew;
i = i+1;
end

subplot(2,1,1)
plot(x,ha,'r',x,hb,'g',x,hc,'b',x,h,'m')
legend('a','b','c','d')
hold on
xlabel('Iterations')
ylabel('HTC')
subplot(2,1,2)
plot(x,dTv)
hold on
xlabel('Iterations')
ylabel('dT')

res=[htca, htcb, htcc, htc, dT];

end

```

A.2 HCMCIA

```

function res=HCMCIA_htc()

Tinf = 294.15; %21 degrees C

k = 0.0278;
rho = 1.106;
cp = 1007;
nu = 1.769*10^(-5);
alpha = k/(rho*cp);
Pr = nu/alpha;
g = 9.81;
As = 0.056274;

```

```

P = 1.7853;
Lm = As/P;
L = 0.2;

Pdiss = 121.52;
Afreea = As;
Afreeb = As;
Afreec = 0.409651;
Afreeav = Afreea + Afreeb + Afreec;
Afree = 0.415571;

htc = 5.7;
i = 1;
diff = 5;

%a) upper surface of hot plate
%b) lower surface of hot plate
%c) vertical plate
%no suffix: weighted average
while diff>0.0000001

    dT = Pdiss/(Afree*htc);

    Tf = (dT+2*Tinf)/2;
    beta = 1/Tf;

    Raab = g*beta*dT*Lm^3/(nu*alpha);
    Rac = g*beta*dT*L^3/(nu*alpha);

    Nua = 0.54*Raab^(1/4);
    Nub = 0.52*Raab^(1/5);
    Nuc = 0.68+0.67*Rac^(1/4)/((1+(0.492/Pr)^(9/16))^(4/9));

    htca = k*Nua/Lm;
    htcb = k*Nub/Lm;
    htcc = k*Nuc/L;

    %weighted average (in respect to free surface)
    htcnew = (Afreea*htca+Afreeb*htcb+Afreec*htcc)/Afreeav;

    diff = abs(htcnew-htc);

    x(i) = i;
    h(i) = htc;
    dTv(i) = dT;
    ha(i) = htca;
    hb(i) = htcb;
    hc(i) = htcc;

    htc = htcnew;
    i = i+1;
end

subplot(2,1,1)
plot(x,ha,'r',x,hb,'g',x,hc,'b',x,h,'m')
legend('a','b','c','d')

```

```
hold on
xlabel('Iterations')
ylabel('HTC')
subplot(2,1,2)
plot(x,dTv)
hold on
xlabel('Iterations')
ylabel('dT')

res=[htca, htcb, htcc, htc, dT];

end
```

B Appendix

Screenshots of the LabView VI for the measurements

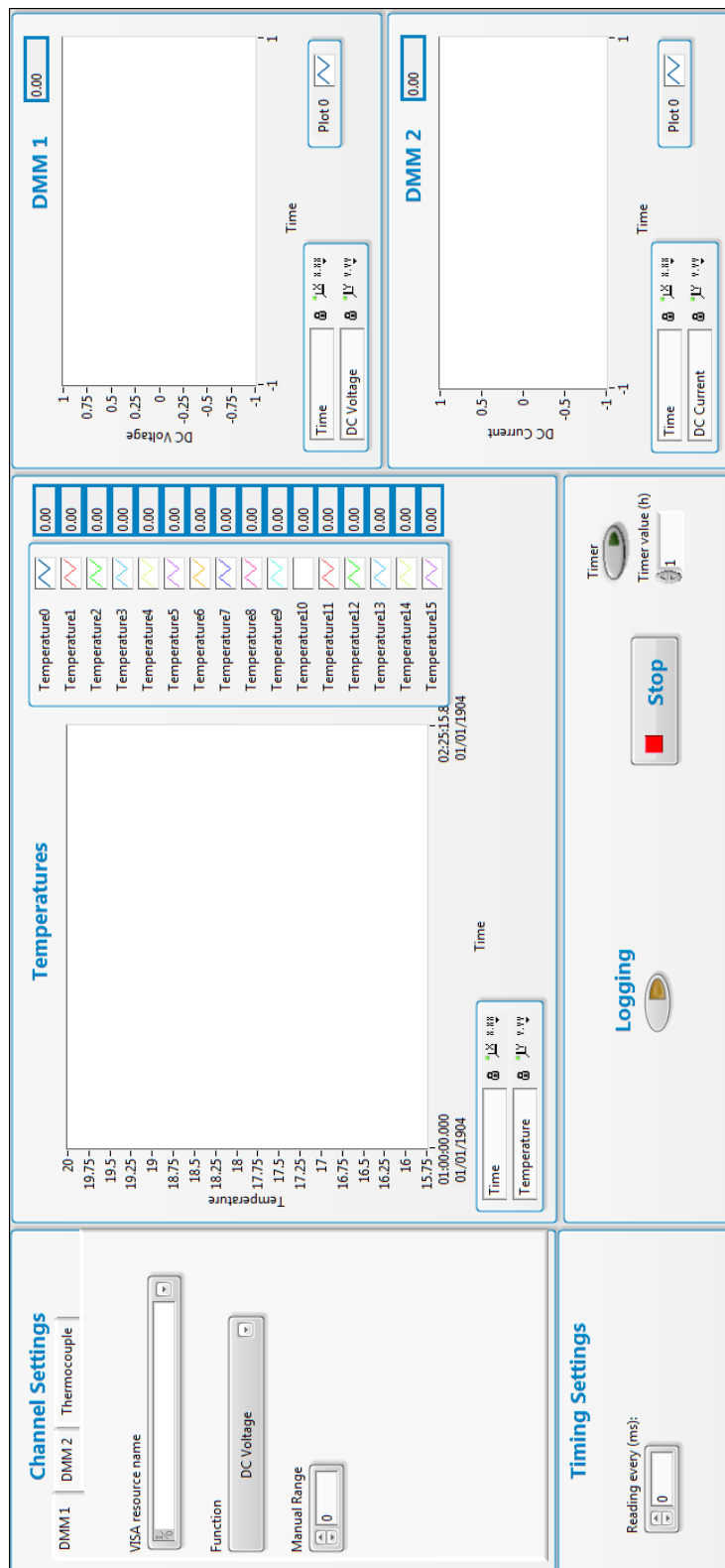


Figure B.1: Front panel of the VI used in the measurements.

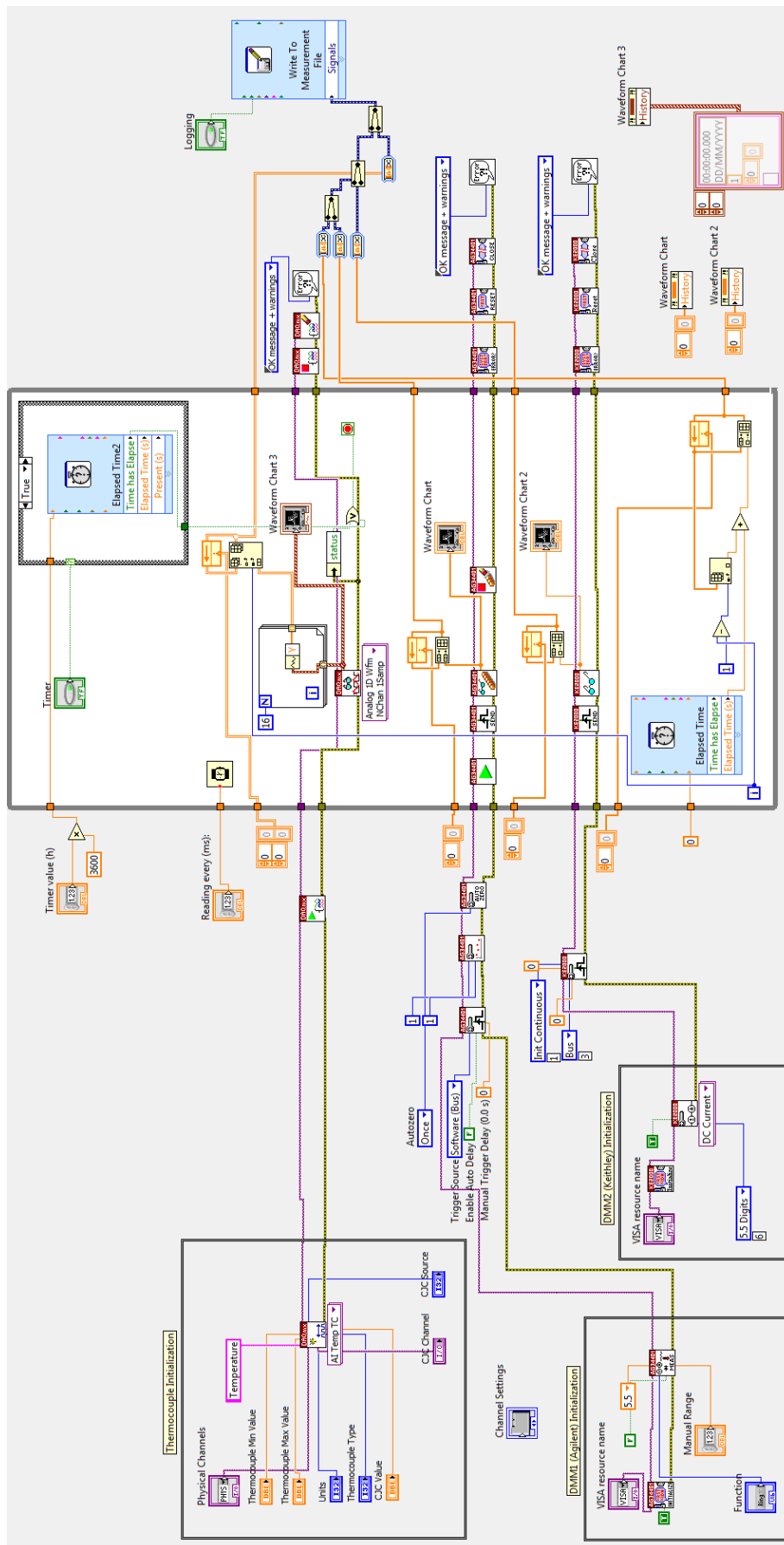


Figure B.2: Block diagram of the VI used in the measurements.