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Finite Element Analysis and Experimental Validation of Underground Transformer Cooling in a Compact Substation

Joseph Mathias Hermann

Universität Duisburg-Essen

Fakultät für Ingenieurwissenschaften

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Erstprüfer Prof. Dr.-Ing. Holger Hirsch

Zweitprüfer Dr.-Ing. Jan Weber

Betreuer Dr. Ir. Jur Erbrink

Betreuer B. Eng. Daan van der Horst

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Master's Thesis Description & Outline

Assignment Title:	Finite Element Analysis and Experimental Validation of Underground Transformer Cooling in a Compact Substation
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Content of Assignment:
The goal is to develop the concept of a micro substation: a substation without medium voltage switchgear (size constraint) and with a recessed setup, i.e. (partially) underground. To achieve this several problems need to be taken into account: How would one design such a transformer space to ensure safety during maintenance, and vandalism? What is the optimal capacity to supply the low-voltage grid? What measures need to be taken to ensure adequate cooling of the transformer? To gain a better overview of the challenges, constraints and wishes from clients, interviews with stakeholders within and outside Alliander can be conducted. Based on the demands of the stakeholders different concepts will be evaluated and refined. The project will then transition to the core of the thesis: thermal management. The thesis, at its core, will focus on one specific question: given the constraints, which cooling measures will ensure adequate load in relation to temperature of the transformer in the substation? A thermal calculation (CFD) of the chosen design will form the basis for a validation test. The proposed test is a temperature-rise test, either (partially) underground or in a representative setup above ground to gain information about thermal and mass transfer phenomena which will be used in validating the model. Concluding testing and model validation the goal is to minimise the required surface area taken up by the station. Thermal calculations will be run to determine if minimising this area is possible while keeping within the set thermal regimes.

Work Packages and Output of the Thesis:

- Literature study of existing works
- Determination of design constraints
- (validated) Thermal CFD model for future engineering
- Practical (temperature-rise) test and results
- Proposed optimal design
- Master's thesis

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Section 161 Negligent false oath; negligent false declaration in lieu of oath

(1) Whoever commits one of the offences referred to in Sections 154 to 156 by negligence incurs a penalty of imprisonment for a term not exceeding one year or a fine.

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Abstract

Originally designed for a relatively low load per customer, the Dutch power grid faces several challenges in its rapid expansion to meet the increasing demand for electrical energy. Beyond smarter grid management, physical reinforcement is essential. In this context, electric substations face numerous deployment challenges in the Netherlands, particularly within densely populated city centres. To alleviate problems in finding suitable locations, the introduction of underground distribution substations has been proposed for areas where classical solutions would otherwise run into lengthy and costly procedures. However, such placement introduces technical hurdles, most notably the critical requirement for effective transformer cooling. This research evaluates potential cooling solutions for underground distribution transformers, while remaining within specifications set by the distribution grid operator, Liander. A computational fluid dynamics model was developed and validated through laboratory testing, to accurately model the top-oil temperature rise of the underground transformer. By linking a simplified transformer model proposed in previous research, with a separate substation model, this approach significantly reduces computational time, enabling the analysis of various cooling and housing geometries. Both testing and the validated model confirm that cooling the transformer is possible in a space-optimized underground vault, while maintaining a 20 K temperature class of the enclosure, resulting in a decreased land use of 63 % and above ground volume by 93 %. Furthermore, it is predicted that a temperature class of 10 K could be achieved if further design optimizations are carried out. This goes to show that cooling underground substations can be managed safely within given standards. Future work remains to investigate safe grid integration, as well as other operating challenges, such as moisture management.

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1. Introduction

The Netherlands has set itself the goal of achieving climate neutrality by 2050, striving for a 50% reduction in CO₂ consumption by 2030 [1]. A key component in meeting these goals is the increasing electrification of households and industry. Here the aim is to replace conventional fossil based energy carriers such as natural gas or oil with renewable, or low carbon, sources. For private households this can be achieved by replacing gas based heating and stoves, with heat-pumps and electric cook-tops; and cars driven by internal combustion engines with electric vehicles [2]. Households may also choose to install their own power generation, usually in the form of photovoltaic panels. These measures can lead to increased peaks in the daily power draw or in-feed to the grid of an household. A sunny day, with low self consumption, will show a large in-feed of the photovoltaic panels during noon. While a cold day in winter will see a large spike from the charging of an electric vehicle, and residential heating when people return home from work.

The increased stress on the power grid resulting from this transformation results in adverse effects on the local distribution grid, whose capacity is no longer able to meet the demand. This change is visible for both consumers and the grid operator. Capacity limitations may force the curtailment of local production and prevent the necessary expansion of connection infrastructure for households, EV charging, and new consumers. While the grid operator sees equipment approaching its current protection limits, or more recently also thermal limits, and the need to reinforce and invest in the grid to prevent further degradation to power and service quality [3]. There are several measures available to increase transmission capacity to the distribution network operator for example: passive measures such as temporarily overloading equipment; as well as active measures such as grid reinforcement and power flow control on the customer side. This work will focus on the expansion of grid capacity through the means of installing extra medium to low voltage (MV/LV) distribution substations, and the challenges faced therein.

1.1. Motivation

Grid reinforcement, by placing substations, is one key component in tackling the shrinking margins in transmission capacity and voltage quality. Realizing these new distribution

substations, however, is becoming increasingly challenging in the Netherlands. Increased load from customers results in larger voltage drop across cables, thereby reducing the effective usable cable length that each substation has, as well as the amount of customers that can be connected to a single cable. The exact amount of extra substations needed to meet this demand is difficult to predict, as it depends on numerous factors, such as the heating strategies, EV penetration and amount of future photovoltaic installations in a residential area. Estimates range from a doubling to quadrupling of the number of substations needed to maintain service quality in the future [2–4]. This expansion is especially challenging in densely populated and built up urban areas, in which space is at a premium. Combined with an increasing public backlash to new substations, and strict rules on public space usage of municipalities (large modern 20kV stations can occupy up to 35 m², with a height over 2 m [5]) lead times to construct additional substations have been steadily increasing [4, 6]. New solutions are needed with which grid expansion fits into city planners regulations, and increases social acceptance, enabling faster electrification of residential areas. One possible solution is by constructing underground substations, eliminating, or greatly reducing the required space above ground.

1.2. Gap in Research

While underground substations exist, their footprint can still be substantial (13-20 m²), and have only recently been going into operation in the Netherlands [5, 7]. In the densest parts of historic old towns, less intrusive and even smaller solutions are needed. For the Dutch market there are currently no trialled, tested, and validated mini-substations on the market. Furthermore, for the purpose of underground substations, currently no construction guidelines, norms, or thermal models exist for applications in Liander's distribution grid. It is known from previous work that placing transformers underground comes with several challenges, the thermal management, while retaining safe moisture limits and maintainability, being one of the most crucial and difficult [8–17]. Much of this work focuses on moving large parts, or the whole, substation underground, with different solutions to aid in cooling of the transformer. The work presented in this thesis is part of a larger project to establish design guidelines for the mini-substations, and will focus on the thermal design, and cooling, of the transformer in an underground vault.

1.3. Methodology

This research aims to create an accurate, validated 3D thermal model of the underground substation and transformer to facilitate future calculations and guide subsequent design decisions. The overarching project is divided into several phases, of which the following are relevant to this study:

1. Concept phase: working together with Liander's department *modulair bouwen* (engineering and development department for substations), a list of requirements will be worked out based on the demands of Liander. Research questions to be answered here include, desired transformer capacity, secondary equipment, public lighting requirements, installation depth, permissible ventilation methods and required thermal class, will be worked out here. **Research question: Which design choices are permissible and logical within the guidelines currently imposed on compact substations?**
2. Simulation: creation of 3D-Models of the cooling concepts, and evaluation via CFD (Computational Fluid Dynamics) simulation. **Research Question: Is it possible to create a coupled model of the transformer and substation and determine relevant thermal parameters from the proposed model, while keeping the calculation time within acceptable limits?**
3. Measure and validate: a representative test will be implemented to validate the simulated thermal design(s) for temperature, airflow and enclosure class. Results of the measurements will be used to improve the model, and lay the foundation for future designs and long term trials. **Research Question: Does the proposed model reflect physical phenomena/reality?**
4. Optimization of the design: the goal is to minimize the required surface area and above ground volume that these substations will occupy, while maintaining adequate thermal performance of the transformer. **Research Question: How small can the needed surface area of a station become while maintaining adequate cooling performance?**

2. Literature Review

Presented here is a quick overview of the structure of Liander's distribution grid, as well as an historic background to explain the current state of the grid. Followed by a literature study of previous work published on underground substations and their challenges. Concluding this chapter is an overview of relevant equations relating to the physics behind heat and mass transfer, as well as methods for modelling these in transformers and substations.

2.1. Liander's Distribution Grid and Challenges

The foundation of Liander's power and distribution grids go back to 1915, with the creation of the *N.V. Provinciale Geldersche Electriciteitsmaatschappij*. The company and its grids grew through several mergers and the liberalization of the European energy market, resulting in the distribution network operator Liander, part of the Alliander N.V.. Liander is currently responsible with the maintenance and administration of the electric distribution grid, and gas lines, in large parts of the Netherlands, shown in blue in Figure 2.1. As a distribution network operator (DNO) in the Netherlands it is their task to maintain, invest in and future proof the gas and electrical distribution grids. In the Netherlands a DNO is responsible for the medium (sub 50 kV) and low voltage sections of the power grid. Liander holds approximately 95.000 km of electric cables, of which 42.000 km are medium voltage (MV, 1 - 50 kV) and 51.000 km low voltage (LV) power lines (<1 kV), both nearly completely underground [18]. While Liander still holds 393 km of high voltage lines, these are in the process of being transferred to the transmission system operator TenneT.

Due to large reserves of natural gas below the Netherlands, energy intensive loads, such as home heating and industrial heat production primarily focused on gas as an energy carrier. The resulting electrical distribution grid was in turn planned and installed for a relatively low current per customer [19]. Topographically the distribution grid of Liander is designed slightly differently on the MV side, compared to the LV side. Medium voltage grids are laid out as meshed networks with occasional branches, and are operated radially. While LV-grids were previously also laid out as meshed grids, and operated radially, modern design guidelines for grid expansion have adopted a full star topology for LV-components [19]. Each MV/LV substation therefore feeds its own

set of LV-connections, with the possibility of switching to alternative supplies if needed. Actual and future load increases on the LV side are causing a number of problems in the grid. Selected problems, and potential solutions will be briefly outlined below.



Figure 2.1.: Map of the regions serviced by Liander's grid operations, shown in blue.
From: [20]

2.1.1. Overloading of Cables

Currents larger than nominal, or above permissible limits in cables lead to two main problems: thermal problems at the cable; and activation of protections (i.e. fuse switch-off), resulting in power interruptions. These can show in different ways for different types of cable insulation, and ground composition. Older PILC (paper insulation lead covered cable) have a conductor temperature limited to 50 °C to prevent accelerated ageing, or breakdown of the insulating material [19]. For modern XLPE (cross-linked polyethylene) insulated cables the maximum conductor temperature is higher, at 90 °C, however long term loading at, or near this temperature can lead to dry-out of the surrounding ground. Dry-out will result in a decreased thermal conductivity of the ground, and therefore also higher cable temperatures, with the possibility of thermal runaway if the load is not reduced, so temperatures must stay below an outer cable temperature of 45 °C. Temperature limits of XLPE cables are therefore often determined by the surrounding ground type (clay, sand, peat), and the temperature on the outside of the cable [19]. Mitigation of these phenomena can be achieved by placing thermally conductive sand around the cable during installation (not commonly done for LV-cables), or reinforcing/replacing old cable runs with new (parallel) lines.

2.1.2. Transformer Capacity

Another capacity bottleneck can be formed by the distribution transformer. Distribution transformers have two major sources of heat: no-load loss, due to magnetization of the

core, and load losses due to currents in the windings (I^2R). Load losses are dependent on the load current, while no-load losses occur as soon as the transformer is at nominal voltage and the core magnetized. Transmission capacity is therefore primarily limited by currents [19]. Depending on the applied duration, and ambient conditions, high currents can also lead to thermal overloading of the transformer. Thermal limits here are primarily imposed by the paper insulation medium [19, 21, 22]. Should temperatures at the paper insulation exceed 98 °C in standard, class 105 °C, insulation, ageing of the insulation will rapidly increase. Although IEC standards specify that normal short-term overloading allows for temperatures up to 120 °C. While the hard limit for this type of insulation lies at 140 °C, after which there is a high chance of irreversible damage to the insulation [22]. Hot-spot temperatures directly in contact with paper insulation must therefore always remain below this limit. As hot spot temperatures are not always measurable, limits on (the measurable) oil temperature are imposed instead. In relation to this IEC 60076-2 specifies a maximum top-oil temperature rise of 60 K and a maximum hot-spot temperature rise of 78 K, at an ambient temperature of 20 °C [21]. Should accelerated ageing be acceptable, or needed to maintain the supply of electricity, overloading of the transformer can be done safely within temperature limits defined in IEC 60076-7. Liander dictates that: should calculations show that a distribution transformer will exceed a load current above 80% of its nominal current, a halt on new connections to the substation is imposed, and a new substation must be built. Current estimates by Liander show a need of doubling to quadrupling the amount of substations, compared to existing numbers, to meet predicted future demand¹.

2.1.3. Voltage Problems

The Dutch grid code demands the following voltage quality for voltages up to 35 kV, and $U_{\text{nom}} = 230 \text{ V}$ in the LV grid [19]:

- $U_{\text{nom}} \pm 10\%$ for 95% of the 10 minute average values per week
- $U_{\text{nom}} + 10\% / - 15\%$ for all 10 minute average values

Problems occur when these limits are violated at points in the grid. A too high voltage will lead to inverters of solar panels switching off, and possible damage to electronic devices. While a too low voltage can lead to flickering lights or certain devices, such as inverters of heat-pumps, shutting down. The source of this issue is usually related to the capacity of transmission lines/cables. A long cable run, with evenly distributed customers along the cable, will see an increasing voltage drop as you go along it. Mitigation of these issues is usually done by passive measures such as: reinforcing the cables, either by installing new runs in parallel or replacing old cables by new cables with lower impedance. Active mitigation can also be implemented by means of installing voltage

¹Source: grid calculations performed internally by Liander

regulated distribution transformers (VRDT) with on load tap changers [23]. The need for these was not always given in the past, as energy would usually be transmitted from the substation to the customers. Voltage problems could therefore usually be alleviated by manually setting the tap to a higher output voltage at the station, to compensate for voltage drop along the line. With increasing power supply from LV-customers to the grid, this is, however, no longer possible, as voltages at the MV/LV-substation could then possibly exceed these limits.

2.1.4. Challenges in Grid Expansion

To meet the growing demand of increasing electrification, intelligent grid solutions are no longer enough, new infrastructure and substations will need to be installed. In the Netherlands, and the areas covered by Liander's distribution grid this expansion is proving especially challenging in densely populated urban centres. In these, available space comes at a premium, and high population densities result in a large amount of connected households, and therefore also large increased demand in the future, should they seek electrification. Ideally new substations are placed as close as possible to the centre of areas in which demand is predicted to increase (see Figure 2.2 for an overview of the situation in a city centre). Attempting to find suitable locations in optimal areas quickly shows first challenges. Most town centres have finished expansion and new construction of housing, therefore the ideal locations for substations are often already occupied. Streets in these old-town centres frequently are also much narrower and/or one way, further restricting available public space. Figure 2.3 shows two typical situations in the city centre of Leiden. Shopping streets (a) may be wider, however the roads must be kept free for emergency and bus access, while pavements need to ensure adequate space for pedestrians. Residential areas (b) sometimes offer parking spaces in which substations could be placed, should the substations footprint allow. Combined with the fact that new substations need to be placed near the predicted demand due to cable length limits, placement becomes difficult and compromises are needed.

Currently two standard solutions are available to Liander for installing new substations in these areas. The first is the compact prefabricated substation. These defined and proven designs are readily available from suppliers and can be installed quickly if space is available. Finding suitable locations in dense city centres for these is, however, challenging, as free unused space is limited. Parking lots are therefore often the most obvious locations. In narrow streets however, placing is often impossible, as the usable road width would decrease to such an extent that access of e.g. emergency services and residents would be restricted, and parking spaces are often not present. Another safety risk when placing these is of the visual kind. Placement in wider shopping or pedestrian streets is often not favoured as it can create hazardous blind spots, or poorly visible areas at night, decreasing perceived safety, and therefore not favoured by residents as

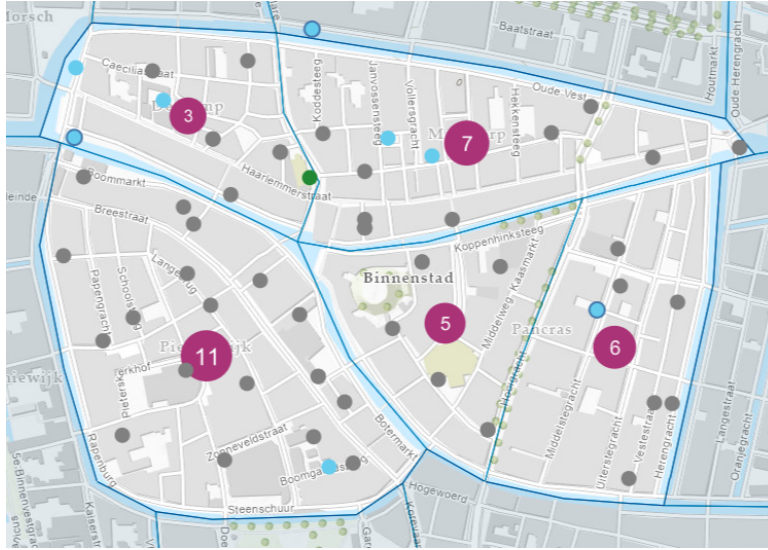


Figure 2.2.: Predicted substation demand for a city centre in the Netherlands. Large purple circles: number of new substations that need to be placed; grey circles: existing substations; light blue circles: substations with the potential to retrofit larger transformers



(a)



(b)

Figure 2.3.: Examples of typical city centre streets in which placing new distribution substations is challenging.

well as the municipality. Placement on wider intersections or corners is not possible due to line of sight impairments, creating dangerous situations for traffic. Finally placement of substations too close to houses can also evoke resistance from residents concerned about e.g. loss of parking spaces, house value or influences of electromagnetic fields [6, 24–28]. Negotiations about location and land purchase are, in the Netherlands, civil matters between the municipality and grid operator. Furthermore no permits are needed for construction of substations under 3 m height and 15 m² [29]. While legal appeals by residents are therefore difficult to impossible, the political relationship between a municipality and its residents can have delaying effects on finding suitable locations [30, 31]. An example of an older compact substation placed in the city centre of Leiden can

be seen in Figure 2.4a. While this station has a small footprint, modern safety and design standards no longer allow for new deployments. As a consequence of this, new compact substations have a significantly larger footprint.

Another possible solution is currently posed by indoor substations. These are usually deployed as a large accessible substation within a building. Designs and specifications for these are available and implementation can be done with relative ease if space has been reserved during construction. Keep-out zones, and requirements that rooms adjacent to indoor substations be not permanently inhabited, are resulting in implementation becoming less favourable with developers, due to the financial downsides. Large challenges, however, become apparent if an indoor station needs to be retrofitted. In building complexes with multiple owners, agreements for construction must be reached with each separate entity, which often leads to lengthy and expensive procedures/negotiations. In the past these have often proven cost and time inhibitive, making the retrofit of indoor substations a last resort option. Figure 2.4b shows a typical situation in which a indoor substation would be deployed in.



(a) Old type of compact substation, no longer placed. (b) Outside of indoor substation. Usually deployed when no space is available elsewhere.

Figure 2.4.: Examples of a compact, and indoor, distribution substation.

2.2. Underground Substations

Both residents, municipalities and Liander's internal engineering teams have in the past expressed their desire for an alternative to the classical compact substations [12, 32]. It was, however, in the past chosen to aim for the standard solutions mentioned above as much as possible to keep costs low and enable fast deployment of substations. The high price of underground MV/LV substations therefore made them cost prohibitive, hence, they were not constructed. Future grid demands do no longer allow for this approach to be sustained, and new options for substations must be investigated. These come with several challenges, as highlighted by Liander's previous trials with an underground substation in the mid 2000's to 2011, and come down to three main problems:

1. Water management: a civil engineering challenge, ground water levels are often high in the Netherlands and underground substations must have sufficient mass/density to counteract buoyancy forces. The concrete housing must also be fully oil and waterproof to prevent groundwater contamination by possible oil leaks of the transformer.
2. Thermal management: placing the transformer underground reduces the amount of available ventilation surface compared to a compact substation. Two examples of this, as described by Lockie and Stewart, are the proximity of the walls severely restricting airflow, leading to re-circulation, and also posing higher ambient temperatures for radiative effects [8, 10]. Care must be taken to ensure sufficient cooling, while still retaining adequate moisture and water management. [12–14, 16].
3. Moisture management: low levels of heat development can lead to unacceptable moisture levels in medium- or low voltage equipment in underground substations, especially when no, or poor ventilation is applied [12].
4. Safety and maintainability: routine maintenance, such as replacing fuses, changing of tap settings, measurements, as well as safety features such as earthing must be able to be conducted according to health and safety guidelines. While still retaining a small footprint.

2.2.1. Heat Transfer in Substations

Heat transfer in substations and transformers happens via three modes: conduction, (natural) convection and radiation [33]. Heat is generated inside the transformers windings and core, as described in 2.1.2. From there it follows a multifaceted path, utilizing all modes of heat transfer. The modes can be described using their respective rate equations.

Conduction

Conduction describes the mode of heat transport inside solid, liquids or fluids via transfer of energy at a molecular level. In fluids this assumes no bulk motion, but only local interactions between molecules of different energy levels due to their random motion. Higher energy (and temperature) molecules colliding with those of a lower energy transfer some of this energy during the collision. Random motion of these molecules will also contribute in the form of diffusion. In solids this conduction happens due to lattice vibrations, and in electrical conductors also due to the movement of free electrons [34]. The rate equation describing a conductive energy transfer in one

dimension Q_x [W], through a wall of area A , width L , conductivity k [W/(mK)], and under a linear temperature gradient ΔT , is [34]:

$$Q_{x,\text{cond}} = k \frac{\Delta T A}{L} \quad (2.1)$$

Convection

Convection describes the mode of heat transfer between a fluid and solids bounding surface at different temperatures, while considering both the effects of conduction and bulk motion in the fluid [34]. In cooling of substations and transformers we also make a distinction between forced and natural convection. We speak of forced convection when fluid motion is driven by external means such as pumps or fans. While natural convection refers to buoyancy induced fluid motion due to temperature, and resulting fluid density variations. Distribution substations are always cooled passively, by means of natural convection, in Liander's grid. The rate equation defining convection, and known as Newton's law of cooling can be written as [34]:

$$q'_{\text{conv}} = h(T_s - T_{\text{amb}}) \quad (2.2)$$

where q' is the convective heat flux [W/m], h the heat transfer coefficient [W/(mK)], T_s the temperature of the solid and T_{amb} the ambient temperature, or temperature of the fluid. Determining h is difficult, as it depends on multiple factors such as the flow field, fluid properties and surface properties, but is crucial to accurate thermal modelling of transformers and substation.

Radiation

Heat transfer by radiation is the transport mode by which two bodies exchange thermal energy via electromagnetic radiation. This radiation is emitted by any body above a non-zero temperature, and does not require any surrounding matter, i.e. also functions in a vacuum. The rate at which radiation is emitted per unit area E [W/m²] depends on the temperature of the body T_s and its emissivity ε , and is limited by the Stefan-Boltzmann constant σ [W/(m²K⁴)] [34]:

$$E = \varepsilon \sigma T_s^4 \quad (2.3)$$

While all bodies, solids, liquids and gasses emit thermal radiation, it is often assumed that gases act as transparent media, and do not participate in radiative heat exchange in models. Radiation phenomena are therefore only calculated for opaque bodies. A special case for the rate equation of a opaque body at temperature T_s , its emissivity ε and its much larger, isothermal surroundings at temperature T_{amb} is given by [34],

where q_{rad} is the radiative heat flux in $[\text{W}/\text{m}^2]$:

$$q_{\text{rad}} = \varepsilon\sigma(T_{\text{s}}^4 - T_{\text{sur}}^4) \quad (2.4)$$

2.2.2. State of the Art

Some of the first works on thermal management of underground pole mounted, single phase distribution transformers, by Lockie, Whirlow and Stewart, with Westinghouse Electric Corporation, [8–10] laid the foundations for future research. These papers discuss the heat and mass transfer phenomena present in an underground vault, establish first lumped element models for distribution transformers in underground vaults, and conduct in situ tests to validate these models. Core findings included: the identification of prevalent heat transfer phenomena, impact of the grounds thermal properties on the thermal behaviour of the transformer, as well as impacts of different ventilation schemes and ambient conditions. They specifically stress the importance of proper ventilation geometries, by the use of flow-splitters to prevent air re-circulation, as well as the potential increase in temperature due to the heating of the walls and earth surrounding the enclosure. This research however focuses on single phase pole mounted transformers of cylindrical geometry, with underground vaults only slightly larger than the transformer. While basic thermal phenomena (conduction and radiation) are similar, geometries and rated power are significantly different compared to distribution transformers used in Europe. Where smaller, single-phase, and lower-power, pole-mounted transformers were discussed in these papers, distribution transformers in Europe are usually larger, three-phase, and ground-mounted.

Liander conducted first trials on underground substations from 2005 to 2011. A prototype underground substation was built and operated in the grid. The design principle here was to place the transformer into an "diving bell" construction to prevent ingress of ground water. The outside of the transformer vault was constructed with heat-fins, to maximize thermal dissipation potential into the ground. Under this sealed condition a 630 kVA transformer had to be de-rated to 350 kVA. At the time the majority of distribution transformers were rated at 400 kVA or lower, making the rating acceptable for grid use [12]. The MV- and LV-compartments were also placed underground, in separate containers for easy access for technicians. These compartments were then held in place by a concrete foundation measuring approximately 5 * 5 m, see Figure 2.5. Testing showed acceptable results overall for transformer thermals, as well as moisture levels in the LV-compartment [12]. The de-rating of a 630 kVA transformer, however, poses a disadvantageous financial decision. Further more, moisture levels inside the MV-compartment, could reach unacceptable levels, as the MV-switch-gear (an EATON Magnefix unit) did not produce enough heat to keep the compartment dry. Unaware of the future drastic need for substations, further implementations of this station were

not preformed due to cost disadvantages compared to standard compact substations, even though overall testing was a success.



Figure 2.5.: Previous prototype of the underground substation. Transformer case left, MV-compartment upper right, LV-compartment lower right (grey). Picture from Liander archives.

Modern commercially available solutions that can fit three phase transformers also exist from multiple manufacturers. Two examples on the European market here are from ZPUE S.A. [35] and Ormazabal [36]. Both of these solutions are realized as compact underground walk-in prefabricated concrete transformer substations. Both share similar depths of approximate 2.8 m, with the ZPUE station being 4700 mm by 3000 mm and the Ormazabal having minimum dimensions of 5140 mm by 2460 mm, or larger, depending on the configuration. While both substation designs fully place the required hardware underground, the walk-in nature still makes them large. A different option, more commonly deployed in Asia and china is designed around an underground transformer vault, with LV- and MV-switch-gear placed in a separate compartment above ground [37]. While exact dimensions are not provided online, pictures of installation with humans for reference show a substantial need for above ground volume, mostly due to the MV-switch-gear.

Numerous mentions of underground substation cooling are made in patents, listed under the IPC (International Patent Classification) description H02B7/08 Underground substations, or H02B7/06 Distribution substations. Solutions to thermal management vary greatly, with designs ranging from partially buried [38, 39], to fully buried with passive- [40–46], or active cooling [47–49]. In solutions that prioritize passive cooling,

a focus is placed on creating flow features which enable, and aid cooling by means of natural convection. Either by placing flow guards/channels or ensuring a height difference between the in- and outlets, to aid the chimney effect. Active cooling solutions however have the benefit of being able to greatly reduce size of cooling channels, as airflow is either forced by a fan, or heat is removed via heat-pumps.

2.2.3. Modelling Methods

Early modelling methods of (underground) substation cooling focused on lumped element models [9, 14, 33, 50–53]. Here, different parts of the thermal path, from source to sink, are represented by an electrical RC analogy. With thermal resistances being presented as resistors, and heat capacities by capacitors. These models offer a computationally light weight, and accurate way of calculating transformer temperatures, while also enabling fast calculations of dynamic loading profiles. The downside, however, is that adjustments to station geometry and ventilation can only be approximated by re-calculating certain resistance nodes. To fully develop an accurate lumped-element model of a substation measurements are needed to validate the separate elements.

Another way of thermally modelling substations and transformer is via computational fluid dynamics [13, 16, 54–57]. Most approaches here create a three dimensional model of the substation and its components, which are then discretized into smaller elements (i.e. meshed). Through choice of physics models, and by imposing boundary conditions onto parts of the model, the equations that need to be solved are defined. The high level of detail, and insight into heat and mass transfer processes that can be achieved using these methods, however, comes at the cost of computational resources, with complex models having solving times of several hours or days [16]. A major challenge in modelling substations this way is posed by the modelling of the transformer and its oil. Two different methods are proposed in literature. The first involves assuming a model of the full distribution transformer, with full, or partially simplified internals, onto which the heat generating boundary conditions are imposed [16, 55, 57]. A second method, developed by J. Gastelurrutia et al. in [55] simplifies the full transformer model into that of a single *slice*, representing a cooling-fin and a fraction of the internal geometries (winding's and core) that form part of this slice. Validation by Gastelurrutia shows that it is possible to accurately model the oil flow and heat transfer phenomena using this model, while reducing the computational resources required. A slight downside to this model however is the need for accurate knowledge of internal geometries of the transformer, provided by either the supplier, or determined by opening the transformer and measuring. Other methods, such as applying a known temperature profile, or modelling the transformer with a uniform heat-flux on the outside can be used, but do not supply information about oil temperatures, but only of airflow in the substation [13, 54].

3. Methodology and Design Conceptualisation

Multiple solutions for the layout, functionality, and thermal calculation exist. For thermal analysis, a CFD focused approach is appropriate, as new geometries need to be tested, and resources for constructing and testing many different geometries are limited compared to calculation time. Design choices for a possible layout and cooling methods, however, are numerous and need to be reduced before starting studies. The following section outlines available options, as well as the weighted criteria behind these to determine first concepts of the underground substation.

3.1. Approach

To find a suitable design for the underground substation, it was chosen to break down and analyse the problem using a morphological chart. The options/solutions were collected from literature studies, interviews with stakeholders and Liander's specifications for distribution substations. Using this chart problems and parameters can be identified. Following this solutions can be proposed and discussed with stakeholders to list pro/contra and possibly exclude certain options completely. Once suitable designs are found in the morphological chart thermal investigation of these can begin. For this purpose COMSOL Multiphysics will be used to simulate the design variations. Results of these first calculations can be used to gauge thermal behaviour of the system. To ensure validity of the models results measurements will need to be conducted on a representative test setup. With this validated model it is possible to create new variations, which can be used for optimization of the designs.

3.2. Design Finding

The goal, at its core, can be reduced to minimizing the required surface area of the underground substation, and its above ground volume. After initial formulation of the problem (placement of a substation underground) interviews with stakeholders were held to identify the options, preferences and boundary conditions for which solutions

needed to be found. The results of Liander's previous trials are taken as a base. It was chosen to start with a concept where only the transformer and low voltage (LV) switchgear are installed locally. By off-siting the MV-switchgear it is possible to reduce the required (public) space, while avoiding moisture issues similar to those encountered in previous trials.

3.2.1. Functions and options

Possible functions and solutions were identified. These can be grouped into four areas: transformer, vault/housing, MV/LV-grid- and auxiliary functions. For the functions of an underground substation the following items were defined:

- **Transformer capacity:** what capacity is needed in future substations, regarding the population dense areas in which they are placed? What limits are there?
- **Depth underground:** how deep should the station be buried, and which parts of the station should be underground? Only the transformer, or also the LV-rack and terminals?
- **Cooling:** what cooling methods are there for the transformer?
- **Transformer tap-changer:** what options are there? Is an on load tap changer desired?
- **Vault Material:** which materials can be used to manufacture the underground vault?
- **MV-Grid Topology:** which solutions exist for integrating the underground substation within the MV-grid safely?
- **MV-Cable:** which types of MV-cable are suitable for connecting the MV side of the substation?
- **Transformer connection:** how will the MV-terminals of the transformer be connected? Which solutions exist that allow feed through to other substations?
- **MV-protection:** How will the MV-side of the substation be protected?
- **Number of LV-Feeders:** how many outgoing low voltage feeders should the LV-side of the substation have?
- **Street lighting and small consumers:** what options are there concerning supply of street lighting and *small consumers* (230 V, $I \leq 6$ A). FlexOVL (Flexible Openbare VerLichting) represents an remote controllable street lighting supply.
- **Generator terminals:** is a terminal for generator infeed needed, and what possibilities are there for connecting this on the LV-side.

- **Telecom:** are telecoms desired, and if so, what options do we want, such as measurements, remote control, etc.?

An overview of the available options was made, based on the information gathered in literature reviews, stakeholder interviews and internal standards, and can be seen in Figure 3.1. From this set of options, potential solutions and designs can be made.

Subsequently different design variations were evaluated. After consulting with engineers from *modulair bouwen* it was chosen to develop three different concepts with respect to final size/volume.

1. **Mini:** The underground substation as compact as possible within the given options. Design choices will focus on reducing required hardware, surface area and volume, both above and below ground to a minimum.
2. **Medi:** an underground substation designed around cooling the most popular transformer (630 kVA) deployed currently. It should include most features a compact substation has, while still moving (parts) of the substation underground.
3. **Maxi:** A larger, walk in option. This design was implemented to meet the space requirements of a city architect from Rotterdam¹. While not as compact as the mini or medium option, it features a more classical layout, potentially reducing required development and engineering time.

Preliminary Scope Reduction

Before working out the above mentioned concepts, certain choices were eliminated to reduce the scope. While these are options available on the market, they are not currently permissible in design guidelines for substations at Liander. A brief outline of eliminated choices, and reasons for doing so is given below, and a morphological chart with the eliminated choices highlighted is present in Appendix A.

- **Transformer capacity:** The options 50-100 kVA and > 1000 kVA were eliminated, as transformers of these dimensions are currently not ordered as standard transformers. Furthermore, with future household connections increasingly going to 3 x 35 A, small transformers would not allow for enough connections per substation. Internal estimates for future demand have shown that a 100 kVA transformer would not be able to supply more than 14 apartments, or 10 units of mixed housing in city centres.
- **Depth underground:** here choice 1 (*not buried*) and choices 4 and 5 (*deeply buried*) were eliminated. Non-buried substations for the given transformer choices already exist, and can be ordered. While *deeply buried* substations (where the

¹Source: internal interview

transformer is located under typical installation levels underground) pose significant civil engineering (buoyancy, foundations) as well as safety (access, earthing, tap changer operation) challenges.

Functions	Solutions					
Transformer capacity	50 kVA – 100 kVA	160 kVA – 250 kVA	400 kVA - 630 kVA	800 kVA – 1000 kVA	> 1000 kVA	
Depth						
Cooling	Dry	Oil Natural	Oil Forced (Direct)	Air Natural	Air Forced	Water Forced
Tap changer	On Load	Manual	None			
Vault Material	Reinforced concrete	Concrete	Steel	Aluminium	Reinforced polymer	
Grid Topology	Radial	Ring	Subring	Branches		
MV-Cable	Al 630 mm²	Al 240 mm²	Al 150 mm²	Al 95 mm²	Cu 95 mm²	Cu 25 mm²
Transformer connection	Screw Terminals	Plugs	Branch cable joint			
MV-protection	Ring main unit off-site	Local fuse	Off-site fuse			
LV-Rails	Few (1-4)	Some (5-8)	Many (9-14)			
Small consumers	FlexOVL	No FlexOVL	None			
Generator terminals	Yes	No				
Telecom	MV-Monitoring	Remote control	LV-Monitoring	None		

Figure 3.1.: Morphological chart

- **Cooling:** Dry transformers were eliminated as these are not in the standard distribution transformer scope. All cooling options with forced cooling were eliminated as these are not permissible for distribution transformers, as to keep maintenance to a minimum. Passive water-cooling by a waterproof transformer submersed in (ground-) water might be possible, but is not currently supported in the standard distribution transformer scope.
- **Transformer tap-changer:** Option *none* was eliminated, as all distribution transformers must have a tap changer according to substation design guides. Furthermore, due to voltage drop in cables, tap changers are needed to ensure an acceptable voltage at customer connections for cable runs of approx. 100 m or longer².
- **MV-Grid Topology:** As integrating underground substations (with no local MV-switchgear) while maintaining switching and safety standards, into a ring topology would not be possible, this option, as well as the sub-ring, was eliminated.
- **MV-Cable:** 630 mm² Aluminium cables were eliminated, as the transformer capacity would not mandate large enough cable diameters given the remaining MV-grid topologies.
- **Transformer connection:** branch cable joints are not allowed for this purpose in current grid design guidelines, so this option was eliminated.
- **Street lighting and small consumers:** as substations must always have the ability to supply public street lights, the *none* option was therefore eliminated.

3.2.2. Design 1: Mini

The smallest of the three options, focusing on keeping the design scope, area and volume to a minimum. The choices were weighed based on maintaining safety, function and serviceability while using minimal space. A morphological chart of the applicable choices can be seen in Appendix A, Figure A.4. A small 250 kVA ONAN (Oil Natural, Air Natural) cooled transformer with a manual tap changer was chosen. This transformer would be compact in size, while still enabling an acceptable number of household connections (approx. 30-50 connections assuming a scenario with heavy electrification and heat pumps³). For the vault a fully buried version, with passive ground cooling was chosen. Earlier studies by Liander had shown that the heat given off by a 400 kVA transformer could be cooled passively, as long as adequate surface area is provided on the outside of the vault. Furthermore this design enables better waterproofing, and eliminates need for ventilation geometries above the ground, further reducing the

²Values based on typical calculations and configurations within Liander's grid.

³Data from internal calculations on future demand scenarios, see Fig. A.7

stations footprint. To ensure adequate cooling the underground vault should preferably be manufactured from metal, such as steel. A cross section of a design study in CAD can be seen in Figure 3.2.

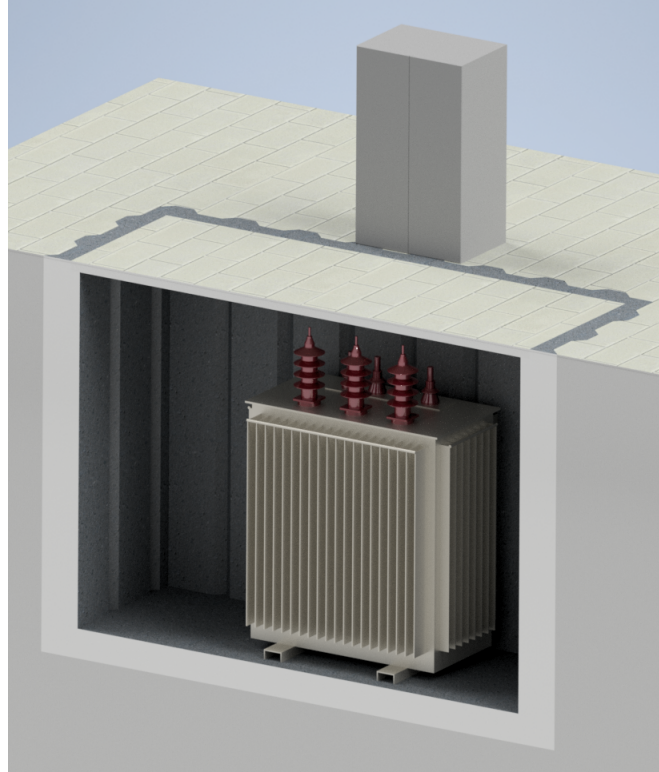


Figure 3.2.: Design study for the *mini* concept

To integrate a substation of this capacity into the grid the topology option for (daisy chained) branches was chosen. Hereby the whole branch is protected by an off site RMU (ring main unit). Connecting this branch could be achieved by using smaller diameter copper or aluminium cables, in proportion to expected load currents and ground properties. Smaller diameters are favourable as they are easier to work with in installation (less stiff) and cheaper. Daisy chaining could be accomplished stacked elbow branch connectors on the primary windings reducing insulation height requirements. Separate MV-fuses per substation should not be included, to maximize space efficiency inside the vault. The LV-distribution cupboard is installed at ground level to enable easy and safe service access. To keep this above ground portion minimal FlexOVL and telecom hardware would not be installed, with only a simple fuse and relay for street lighting supply. The minimum of 4 low voltage NH00 groups would be installed. This dimension of LV-rack would enable the hookup of the feeding transformer, a generator, as well as two outgoing rails for customer supply.

3.2.3. Design 2: Medi

The transformer choice for the *Medi* concept fell on a 630 kVA unit. Transformers of this size are standardized as *norm-transformers* by Dutch DSOs, are a common unit placed in cities⁴, and offer a good balance between size and rated power. A manual tap changer is included, but a on-load tap changer would be preferable. Deployment of an on-load tap changer would enable not only a better management of cable voltages at customers and the substation, but also increase the LV-cable length for connections to the substation. A positive side effect of this is that the area of interest in which a distribution substation is deployed increases (as longer cables are possible), enabling greater flexibility in finding suitable locations.

The cooling configuration is ONAN, with ventilation openings in the underground vault. These openings can be configured in different geometries, with flow guides or vertical height differences aiding in the creation of a chimney effect. While designs of this type are more difficult to engineer with respect to environmental challenges than the *mini* design. The improved transformer thermals by air cooling are substantial and enable higher grid capacities, with fewer deployed substations. Three different ventilation geometries were sketched as concepts. The first concept has separate in and outlets directly above the vault, a design which was proven to work in a similar substation in [13]. The second offers a combined in and outlet, split by a flow guard, reducing the amount of openings needed in the lid. While the third concept involves placing the in and outlets to the right and left of the housing of the LV-rack, resulting in a compact single unit above ground level. A design study of concept one can be seen in Figure 3.3, while the other options are listed in Appendix A, Figure A.1, A.2. As the vault's walls are not solely responsible for removing the heat, it was chosen to go with concrete walls, as these are easy and cheap to manufacture and offer excellent environmental resistance (i.e. corrosion) compared to a steel vault, and do not become energized easily if there is an (insulation) failure inside the substation.

Grid integration would be accomplished as a single radial branch from an existing (distribution) substation, in which an off-site RMU would handle the MV-protection. Local MV-fuses can be installed if desired. The LV-connection would be appropriately sized at around eight NH00 groups, enabling good use of the transformers capacity for outgoing connections, as well as space for a generator connection for backup power supply. Housing the eight LV-feeders would be accomplished by an above ground distribution cabinet. This would also be large enough to fit extra equipment for FlexOVL, enabling the dynamic switching of low-current loads and street lights. Another opportunity offered by a larger cabinet above ground is the possibility of installing earthing connections for the MV-terminals of the transformer in the cabinet, or a possible local disconnect of the MV side. This would grant a large safety improvement when needing to work on

⁴Source: internal data on deployed transformer capacities.

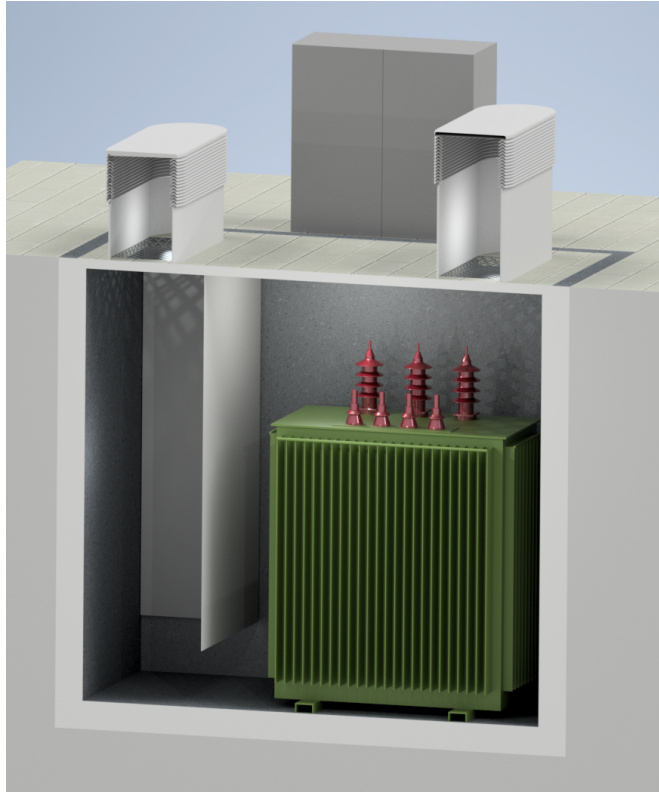


Figure 3.3.: Design study for the *Medi* concept, *box-setup*

the transformer, allowing for a visibly earthed, or disconnected point, which is easily accessible. This is also a requirement from Liander’s specifications for work safety. A morphological chart of the presented choices can be seen in Appendix A, Figure A.5.

3.2.4. Design 3: Maxi

City councils and city architects have, in the past, expressed the desire for a compact substation which is (partially) underground, with a maximum height of 1.4 m and fits into the footprint of a standard parking space (2 m wide by 5.5 m long for a parallel spot [58]). Using these space restrictions as a basis the choice was made to go for a partially underground design, with a space for a transformer equal to or greater than 630 kVA to ensure the possibility for reinforcement in the future, see Figure 3.4. As more space is available for auxiliary equipment in this design, the transformer can be equipped with a (remote controllable) on load tap changer. Cooling would be ensured by large louvres placed on the sides of the above ground housing. While the housing could be manufactured using concrete, akin to existing substations. A door with stairs for entry would also enable safe access to the transformer for maintenance.

Connection and integration into the grid would be handled in a way akin to that of the *Medi* design, utilizing an off-site RMU and a radial grid layout. The extra space in

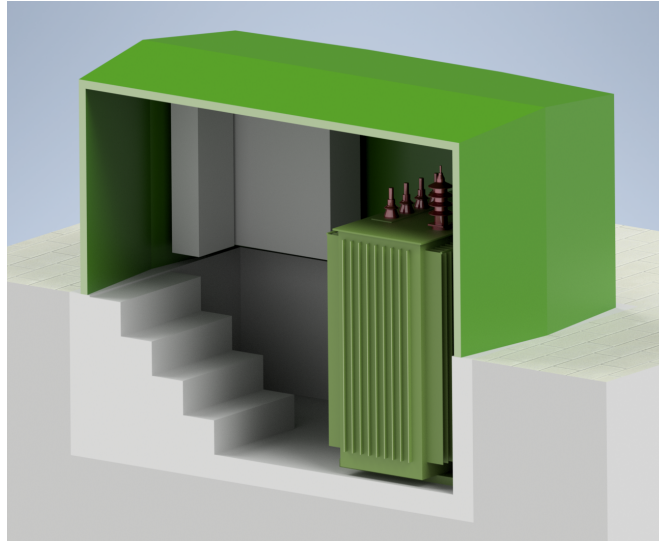


Figure 3.4.: Design study for the *maxi* concept

this substation would also allow for easier mounting of local fuses on the transformer. Earthing the transformer for inspections, or manual tap changer operation is also much simpler to integrate in this design, compare to the *Medi* and *mini* variants. Furthermore doors can be integrated such that quick access of LV-equipment is possible from the outside. Theses can be substantially larger than in the previous designs, and telecom and secondary hardware for measuring the LV-side currents and voltages, transformer temperature, or tap-changer control can be fitted. The design choices are presented in a morphological chart in Appendix A, Figure A.6.

3.3. Final Designs

The different designs were then further evaluated with engineers from *modulair bouwen*. Input was provided for feasibility of the different designs, and it was chosen to not further pursue the *mini* and *maxi* designs. The mini design does not offer enough transformer capacity for future grid expansion needs, nor does it allow for easy access, remote monitoring of transformer condition, or time adjustable street lighting. Furthermore, a vault made from metal would be prone to corrosion, and may become energized in case of an earth fault. All of these factors combined made it an unsuitable candidate for a future underground standard compact substation. The *maxi* design on the other hand faced the downside of being too large. While placement within parking spaces would be possible, finding these in the needed locations is also not always possible (see the absence of parking in Fig. 2.3a), and therefore it would only pose a partial solution.

It was therefore chosen to further focus, and develop the design, and cooling dimensioning of the *Medi* station. This station offers a balance of transformer capacity and footprint.

As the chosen cooling designs need to be validated, and testing time in the laboratory would be limited, it was chosen to reduce the design scope to two options. The first option is the ventilation design shown in Figure 3.3, which was named *box-setup*. It is known that a larger underground substation developed by Ramos et al. in [13] can adequately cool an underground transformer. What is unknown however is how small the vault and ventilation openings can be made. It was further chosen to pursue the cooling towers integrated in the distribution cabinet, shown in Figure A.1, named the *cabinet-setup*. This design was promising as, next to a compact footprint, it would also offer a small above ground volume, with cooling and electrical equipment combined into one cabinet. These concepts will henceforth be referred to as a mini-substation (mini-Middenspanningsriimte) mMSR for short. Before engineering and implementation of these designs can start, it is however crucial to investigate the thermal performance of these designs. This process will be divided into three steps (implementation, evaluation and optimization/improvement), described in the following chapters.

4. CFD Simulation

To provide a first analysis for the cooling performance of the chosen mMSR designs, a coupled 3D computational fluid dynamics and heat transfer simulation in COMSOL Multiphysics was implemented. The software suite offered by COMSOL enables the calculation of physical problems via a finite element approach and solver. Relevant to this study, it enables the solving of coupled multi-physics problems involving the transport phenomena present in transformers and substations. Utilizing this, it is possible to accurately capture and model the heat and mass transfer phenomena present in underground substations. All simulations presented in this study were calculated in COMSOL Multiphysics version 6.2. This section will describe the process followed, starting with an outline of the physics used followed by the studied geometries, their meshes, model implementation and results of first calculations. The goal is to create a model with which it is possible to predict the transformers top-oil temperature inside the underground substation, while keeping the calculation times within acceptable limits.

4.1. Utilized Modelling Techniques and COMSOL Physics Nodes

The basis for simulating heat and mass transfer in the underground substation is given by the models developed by Gastelurrutia et al. in [55] and Ramos et al. in [13], who developed a transformer and substation model respectively. While the *slice*-model formed the basis for the transformer model in this work, the substation models by Ramos et al. were significantly different to the ones in this work, and used as a basic approach to the model. Each model was first implemented separately, and later linked by shared boundary conditions.

Capturing the heat and mass transfer phenomena of a substation required the use of multiple different physics modules within COMSOL. The basis for this simulation is the *Heat Transfer in Solids and Fluids* module, in combination with the *Radiation* module. Fluid flows were calculated using a *Turbulent Flow* module, with two different turbulence models, and linked by the *Nonisothermal Flow* module. Detailed derivations and explanations of the physics and equations used within COMSOL can be found in the respective CFD and Heat Transfer Module Users Guides [59, 60]. A quick overview

of the used multi-physics modules, and relevant equations solved is given bellow. Only the base formulas will be presented. Alterations that happen to these due to solver settings can be found in the relevant modules user guides [59, 60, 64]

4.1.1. Nonisothermal Flow

According to the COMSOL documentation the Nonisothermal Flow interface solves for "conservation of energy, mass, and momentum in fluids and for conservation of energy in solids" [64]. These are based on the Navier-Stokes equations (shown here in the general form according to Eq. 13-1 - 13-3 [64]), in order: conservation of mass, momentum and energy (in terms of temperature):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (4.1)$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot [-p \mathbf{I} + \mathbf{K}] + \mathbf{F} \quad (4.2)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T \right) = -(\nabla \cdot \mathbf{q}) + \mathbf{K} : \mathbf{S} - \frac{T}{\rho} \frac{\partial \rho}{\partial T} \bigg|_p \left(\frac{\partial p}{\partial t} + (\mathbf{u} \cdot \nabla) p \right) + Q \quad (4.3)$$

where the COMSOL documentation defines the symbols, and their SI units as [64]:

- ρ , density [kg/m³]
- $\mathbf{u}$, velocity vector [m/s]
- p , pressure [Pa]
- $\mathbf{I}$, identity matrix [unit-less]
- $\mathbf{K}$, viscous stress tensor [Pa]
- $\mathbf{F}$, volume force vector [N/m³]
- C_p , specific heat at constant pressure [J/(kg K)]
- T , absolute temperature [K]
- $\mathbf{q}$, heat flux vector [W/m²]
- Q , heat sources [W/m³]
- $\mathbf{S}$, strain rate tensor:

$$\mathbf{S} = \frac{1}{2} \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right) \quad (4.4)$$

These equations are altered depending on chosen boundary conditions or constraints. Changes to the equations are described in detail in COMSOL's documentation [64].

4.1.2. Heat Transfer with Surface-to-Surface Radiation

When considering radiation, $\mathbf{q}$ includes a radiative heat flux on participating boundaries. COMSOL considers the following net inward radiative heat flux, q [W/m²] for an ideal grey opaque body (Eq. 4-98 [60]):

$$q = (1 - \rho_s)G - J \quad (4.5)$$

where G is the total incoming radiative flux (irradiation) [W/m²] and J the total diffuse outgoing radiative flux (radiosity) [W/m²] at a point P, and ρ_s the specular reflectivity [60]. The radiosity is defined as "the sum of diffusively reflected and emitted radiation:" (Eq. 4-97 [60])

$$J = \rho_d G + \varepsilon e_b(T) \quad (4.6)$$

where $e_b(T)$ is the power radiated across all wavelengths dependent on the temperature T [K], ε the emissivity, and ρ_d the reflectivity. For an ideal grey body (equal absorptivity and emissivity), q simplifies to (Eq. 4-101 [60]):

$$q = \varepsilon(G - e_b(T)) \quad (4.7)$$

4.2. The Transformer Slice Model

As part of their research into modelling substation thermals Gastelurrutia et al. worked on reducing the needed computational resources by simplifying the whole transformer model. Instead of having a computational domain encompassing the whole transformer, and therefore needing to resolve flow over many features (windings, fins) they chose to reduce the transformer to a single representative *slice*, encompassing a single cooling fin, as well as parts of the core and windings, as shown in Figure 4.1. The computational domain of the slice model takes into account only the fluid domain, and does not model any solid domains. Evaluation of this model by Gastelurrutia et al. on three different transformers and comparison with measurements showed good agreement [55]. It is therefore suitable for determining top-oil temperature, but not for a more detailed analysis of e.g. hot spot locations within the windings.

A detailed explanation of the model and relevant derivations can be found in Gastelurrutia et al. [55], specifically regarding discussions of turbulence modelling, and application of convective boundary conditions to the fin, which would go beyond the scope of this work. As Gastelurrutia's model was implemented in ANSYS Fluent, some deviations had to be made in this study.

To start with the construction of a slice model, detailed information about the transformers internal dimensions is needed. As the transformer available for testing was of

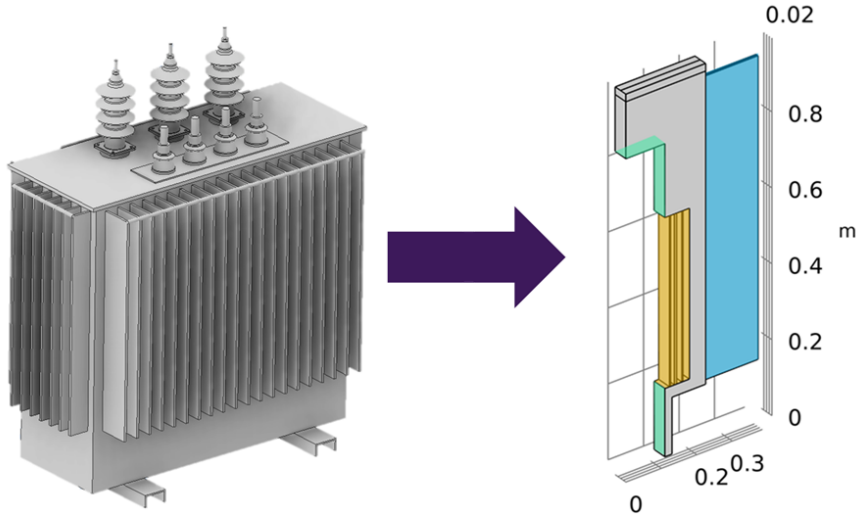


Figure 4.1.: Illustration of the *slice* model according Gastelurrutia et al. [55]. A central fin is "cut" out of the transformer, and only the oil domain is modelled.

an older type, and detailed drawings could not be obtained it was chosen to open the transformer in the lab, and manually measure and determine the relevant geometric dimensions see Figure 4.2. These dimensions include: winding height, width, positioning; dimensions of the cooling channel, dimensions of the core, and positioning of the core inside the tank; as well as dimensions of the tank and cooling fin, such as: height width, depth, and the thickness of the steel housing.



Figure 4.2.: Removed transformer internals for measurement.

Once relevant dimensions had been obtained modelling in COMSOL could start. The

geometry was implemented as a parametric 3D-geometry inside COMSOL. The thickness of the *fin-slice* is equivalent to that of the centre distance of two fins. Internal structures such as connectors between the windings and terminals were omitted. The fins were also simplified to rectangular blocks, omitting the pinched welds at the top and bottom of the fin. In contrast with the transformers used by Gastelurrutia et al., no paper flow guides were present in the windings cooling channels of the transformer used in this study. Parts of the geometry were also sectioned off to allow for extraction of thermal parameters, such as the temperature profile on the outside, or top-oil temperatures. While this did not have an effect on the geometry itself, it will later lead to meshes constructing such that nodes fall onto these boundaries.

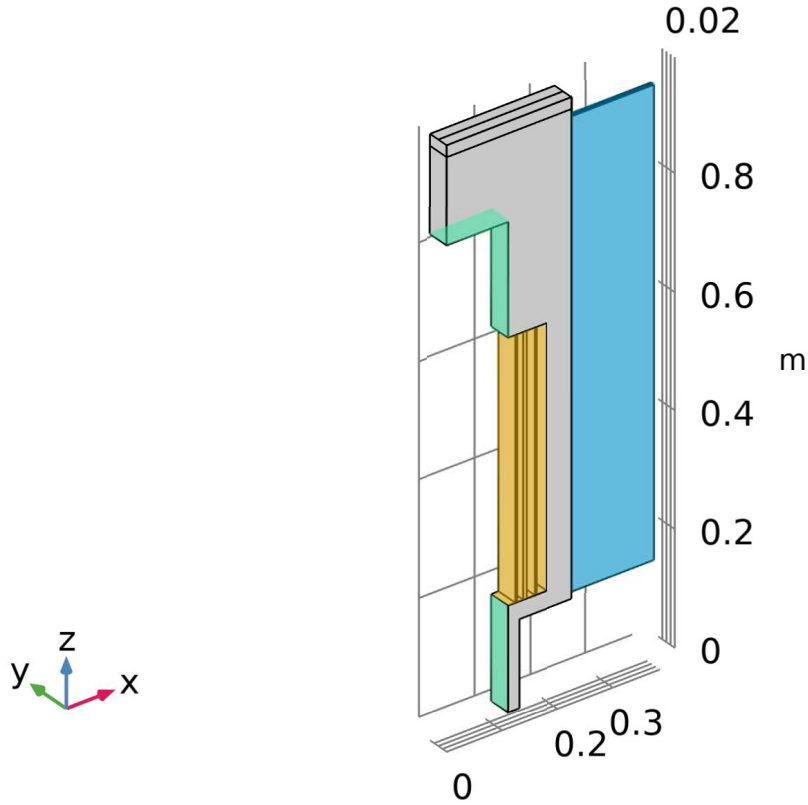


Figure 4.3.: The *Fin-Slice* model, based on the Pauwels Transformer

4.2.1. Boundary Conditions

Boundary conditions were imposed to be similar to those by Gastelurrutia et al. To model the physics a *Heat Transfer in Solids and Fluids* module was linked to a *Turbulent Flow* module via a *Nonisothermal Flow* node in the COMSOL solver structure. Boundaries without manually assigned boundary conditions were treated as thermal insulation (Fig. D.2).

Materials

Two materials were assigned to the computational domain. The COMSOL supplied *Transformer Oil* material was assigned to all domains, (see appendix Fig. D.1a). This material has temperature dependent material properties for the dynamic viscosity, thermal capacity, thermal conductivity and density. It is representative of the transformer oils used in the field by Liander. *Structural Steel* was assigned to the boundaries on the outside of the fin, Figure D.1b. The *Structural Steel* material has constant material properties, thermal conductivity was set to 50 W/(m K) akin to Gastelurrutia et al, heat capacity was 475 J/(kg K) and density was 7850 kg/m³.

Steel Transformer Housing

To model the steel sheet housing of the transformer, the sides of the *fin-slice* model that would be in contact with ambient air were modelled as a thermally thick boundary, see Figure D.1b for location and thickness. This adds a thermal resistance, equivalent to a layer of material of certain thickness, between the internal volume and external heat transfer boundary conditions, in time dependent simulations the thermal capacity is also considered [60].

Symmetry

Symmetry planes were implemented according to Gastelurrutia et al., on the two lateral planes and the rear planes, in both the *Heat Transfer* and *Fluid Flow* domains, see Figure 4.4c.

Heat Sources

Heat sources were modelled as constant, uniform heat fluxes q in W/m² assigned to the boundaries where oil would be in contact with the core or HV-/LV-windings, see Figure 4.4d - 4.4f. The formulas for calculating the respective q are given by Gastelurrutia et al. in [55] as:

$$q_{\text{Core}} = \frac{P_{\text{N,Core}}}{A_{\text{Core}}} \quad (4.8)$$

$$q_{\text{i,LV}} = \frac{P_{\text{N,LV}} \cdot (V_{\text{i,LV}}/V_{\text{Tot,LV}})}{A_{\text{i,LV}}} \quad (4.9)$$

$$q_{\text{i,HV}} = \frac{P_{\text{N,HV}} \cdot (V_{\text{i,HV}}/V_{\text{Tot,HV}})}{A_{\text{i,HV}}} \quad (4.10)$$

Each heat flux represents a fraction of the power loss in the relevant component (P_{N}) divided by the surface area of the respective component A . The LV-/HV-fluxes are

further multiplied by the volume of copper in a single coil V_i divided by the total volume of copper in the coils V_{Tot} . As all respective coils of the different phases were of the same volume, this was equal to multiplying by 1/3rd. Exact power losses of the transformer were unknown during the initial creation of the model. Empirical values of a standardized *norm*-transformer were therefore taken as an initial estimate, with an assumed 50/50 split of the HV-/LV-losses. The values used and calculated heat fluxes can be seen in Table 4.1. These values were later refined with the actual values obtained by measurements in Chapter 5.

Table 4.1.: Estimated losses and calculated heat fluxes

Component	P_N [W]	q [W/m ²]
Core	540	227.66
LV	2300	497.81
HV	2300	418.03

Convective Boundary Conditions

Gastelurrutia et al. stress the importance of evaluating the convective boundary conditions on the fin, not as a constant, but varying within the z-axis¹, and re-computing it at the coordinates corresponding film and ambient temperatures [55]. The convective boundary conditions present in COMSOL allow for this, and were implemented as natural, external convective boundary conditions according to [60]:

$$-\mathbf{n} \cdot \mathbf{q} = h(T_{\text{ext}} - T) \quad (4.11)$$

where $\mathbf{n}$ is the normal vector of the surface and $\mathbf{q}$ vector of the heat flux through it. h , the heat transfer coefficient, is dependent on parameters such as: external material properties (density, viscosity, thermal conductivity, etc.), characteristic length scales L [m], as well as dimensionless numbers such as the Prandtl (Pr), Grashof (Gr_L) and Rayleigh (Ra_L) numbers. As density depended only on temperature, the according formulas for this case were used [60]. These dimensions or numbers were evaluated locally and calculated differently for the different areas and geometries of the fin, assuming an ambient material *air* and an ambient temperature $T_{\text{ext}} = T_{\text{amb}}$. Furthermore according to the COMSOL documentation, ambient "material properties are evaluated at $(T + T_{\text{ext}})/2$ " (the film temperature), where T is equal to the temperature at the wall, fulfilling one of the requirements set by Gastelurrutia et al. [55, 60]. We can differentiate between two main convective geometries, that of a horizontal plate, such as the transformer's lid, and that of a vertical plate, for example the fin.

¹z-axis in this work corresponds to the y-axis in [55]

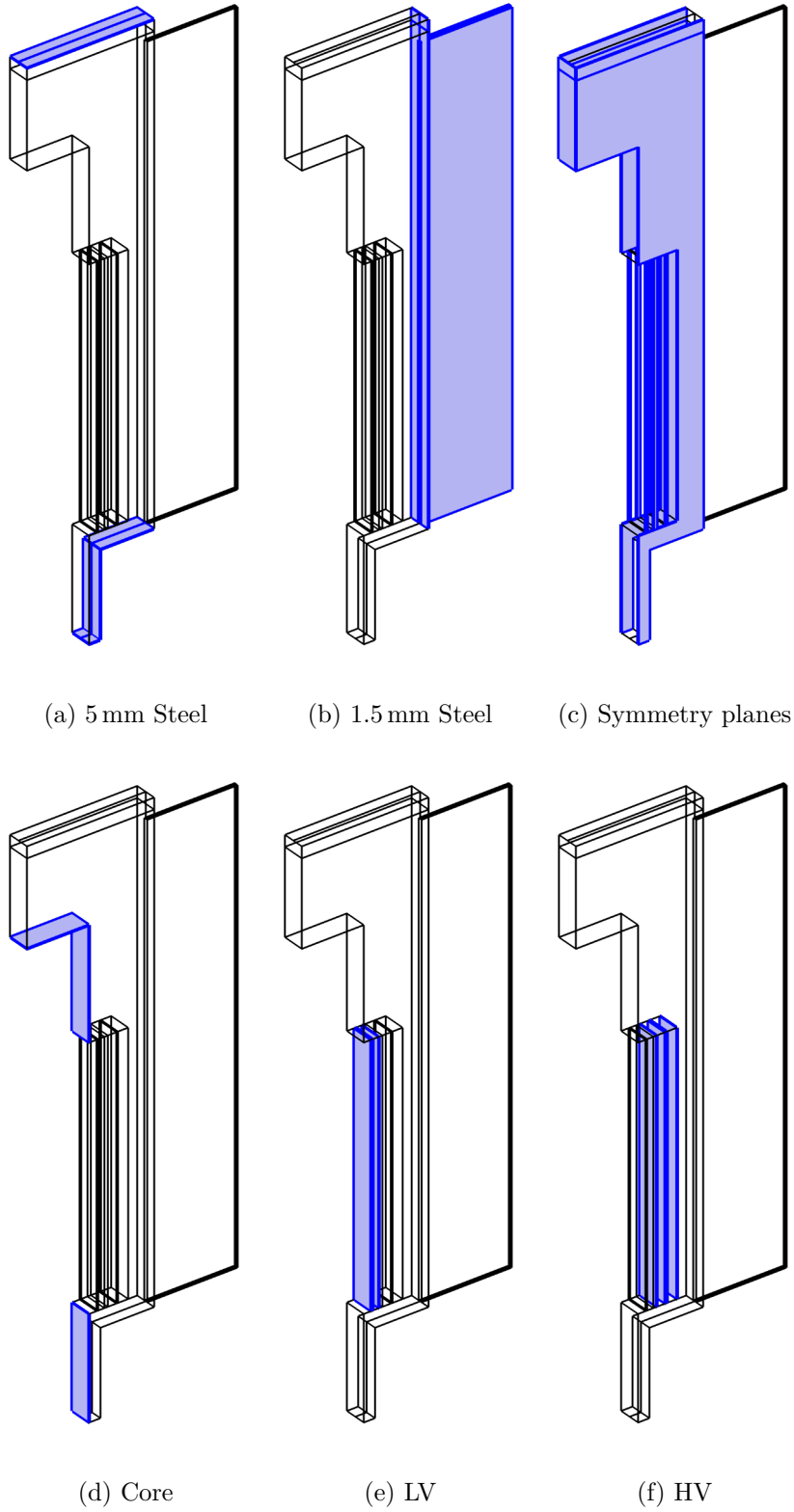


Figure 4.4.: (a-b): Thin layer steel approximation; (b): Symmetry planes; (d-f): Heat sources of the *fin-slice* model.

For horizontal boundaries COMSOL calculates the convective heat transfer coefficient h using equations (9.30 - 9.32) in [34], and according to the given conditions of T (wall temperature) and Ra_L , where Ra is the Rayleigh number, evaluated for the characteristic length L . Horizontal boundaries can be seen in Figure 4.5 (a) to (c) and were:

1. **Lid:** convective boundary condition for the case *horizontal plate, upside*, with a characteristic length of:

$$L = \frac{A_{\text{Lid}}}{P_{\text{Lid}}} \quad (4.12)$$

where A_{Lid} is the surface area of the transformer's full lid, and P_{Lid} the perimeter, see equation 9.29 in [34]. See Fig. 4.5a.

2. **Tank Undersides:** assigned to the horizontal area at the bottom of the transformers heat sink tank. Convective boundary condition for the case of *horizontal plate, downside*. The characteristic length was evaluated as:

$$L = \frac{A_{\text{Tank,Bot}}}{P_{\text{Tank,Bot}}} \quad (4.13)$$

where $A_{\text{Tank,Bot}}$ is the area of the underside of the full transformer, and $P_{\text{Tank,Bot}}$ the equivalent perimeter. The equations evaluated for h are the same as in 1. Lid (9.30-9.32). However, as the geometry here represents a hot *downside* equation 9.32 will usually apply. See Fig. 4.5b.

3. **Transformer Bottom:** representing the bottom of the transformer and also assigned the convective boundary condition *horizontal plate, downside*. The characteristic length was defined as:

$$L = \frac{A_{\text{Transf.,Underside}}}{P_{\text{Transf.,Underside}}} \quad (4.14)$$

where $A_{\text{Transf.,Underside}}$ is the area of the horizontal underside of the transformer and $P_{\text{Transf.,Underside}}$ the equivalent perimeter. The equations were evaluated akin to *Tank Undersides*. See Fig. 4.5c.

Vertical geometries were implemented as a convective boundary condition for the case *vertical wall*. COMSOL calculates h using equations 9.26 and 9.27 in [34, 60]. These were then assigned to the following boundaries, seen in Figure 4.5 (d) and (e), and characteristic lengths where defined as follows:

1. **Fin:** Assigned to the vertical sections of the cooling fin. The characteristic length L was set to the height of the fin (the height of the vertical wall) at 0.8 m. See Fig. 4.5d.
2. **Tank Vertical:** Assigned to the vertical section of the transformer's tank. L was set to 0.995 m, the height of the transformer. See Fig. 4.5e.

Radiative Boundary Conditions

Boundaries in contact with ambient at normal directions were modelled as having a radiative component. The boundary condition applied assumes an ideal grey body, i.e. emissivity and absorptivity are equal, and the surface heat flux due to radiation given by:

$$-\mathbf{n} \cdot \mathbf{q} = \varepsilon \sigma (T_{\text{amb}}^4 - T^4) \quad (4.15)$$

where ε is the emissivity of the surface and was set to 0.9, σ the Stefan-Boltzmann constant, T_{amb} the ambient temperature and T the surface temperature [60]. The locations to which this boundary condition was applied to can be seen in Figure 4.5f. It was not applied to the sections of fin facing other fins, as these would have similar temperatures, net heat transfer due to radiation between them would be minimal ($T_{\text{amb}} \approx T$, emitted temperature is similar to the surrounding fins).

Flow Domain

As the *fin-slice model* restricts itself to modelling only the fluid part of the transformer all geometric domains are also flow domains. Gastelurrutia et al. performed an analysis of different turbulence models in [55]. Two core findings are that a resolution procedure up to the walls is important to better capture heat transfer effects at these, and that all of the tested turbulence models (RNG $k-\varepsilon$ and Low Reynolds $k-\varepsilon$) show satisfactory performance, with the RNG $k-\varepsilon$ model coming ahead slightly in their conclusion. As this model was not available in COMSOL it was chosen to adapt the Low Reynolds $k-\varepsilon$ model implemented in COMSOL, outlined in [59, 61]. Exterior walls were treated as no-slip.

As computational resources, both processing power and time, were greatly limited² it was decided to implement the flow regime as an incompressible flow, with the Boussinesq approximation. Under this approximation, all material properties are assumed as constant (at a specified reference temperature and pressure), and only density variations contribute to buoyancy effects [34, 59].

The application for this approximation for transformer oil does not come without risk. First, temperature variations inside transformers fall outside the range inside which its application is recommended ($\Delta T < 20 \text{ K}$) [34, 62]. Secondly, while most material properties of transformer oils do not vary much with temperature, viscosity does so strongly [63]. A comparison between different flow regimes (incompressible with Boussinesq approximation and weakly compressible flow), was done to discern the effects on computation times, and temperatures, and can be seen in Appendix C. As the

²As only one COMSOL license was available at Liander, calculation times were usually limited to 16 h a night, or 64 h per weekend during which a single calculation had to be completed.

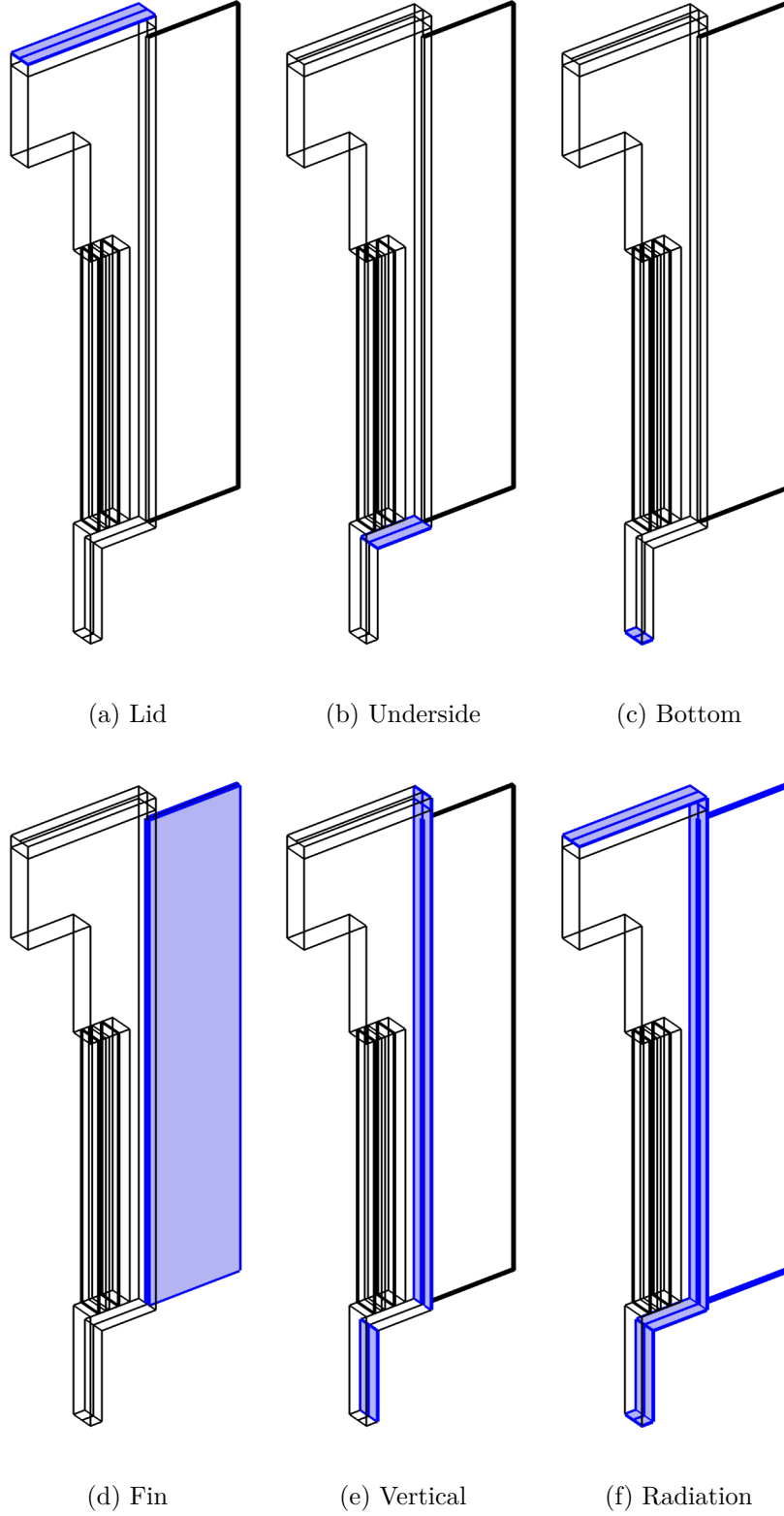


Figure 4.5.: (a-c): Horizontal convective boundary conditions; (d-e): vertical convective boundary conditions; (f): radiative boundary conditions of the *fin-slice* model.

incompressible flow with the Boussinesq approximation at a reference temperature of 293 K showed greatly reduced computation times, while maintaining acceptable thermal performance it was chosen to continue with this for calculations in this work. Should more computational resources become available in the future it is strongly recommended to apply a flow regime not utilizing the Boussinesq approximation.

To ensure a defined pressure in the system, a pressure point constraint of 0 Pa was applied at the lowest point of the model, and at the centre of the fin see Figure 4.6.

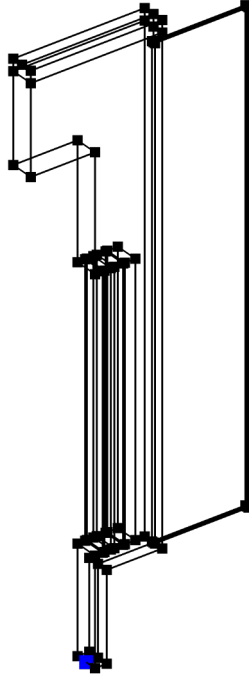


Figure 4.6.: Pressure point constraint of the *fin-slice* model.

Nonisothermal Flow

The *Nonisothermal Flow* multi-physics node was used to link the heat and mass transfer with the fluid flow physics. Under this the Boussinesq approximation was enabled, and the reference temperature and density were specified by the heat transfer interface, $T_{\text{ref}} = T_{\text{amb}}$.

4.3. The Vault Model

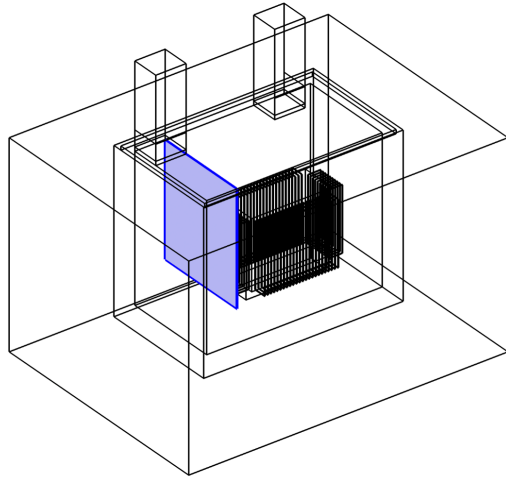
To model the vault of the underground substation a simplified geometry of the substation, transformer, air and surrounding earth was implemented. The vault of the substation

was implemented as a shelled concrete housing, with walls 150 mm thick, and a length x width x height (l x w x h) of 2500 mm x 1500 mm x 2000 mm. These dimensions were larger than what was needed to fit a standard 630 kVA transformer inside a transformer compartment of a compact substation, which usually give approx. 25 mm space on each side of the maximum dimensions specified for a standard 630 kVA distribution transformer (l x w x h: 1500 x 890 x 1800 mm). As the transformer used in chapter 5, had, at the time, not yet been made available, the space was kept large enough to potentially fit the 1000 kVA transformer available for experimental testing inside the high-voltage laboratory. The compartment therefore fit a standard 630 kVA transformer with 200-300 mm to spare on the length and width. Whereas in a standard compact substation deployed by Liander this is often just several centimetres (20-50 mm). The height/depth of the vault had also not yet been defined, and was made deeper than needed to potentially fit a transformer with 20 kV insulators, as well as leaving space underneath for an oil catch pan or grating upon which the transformer could be placed. An wire-view of the *cabinet-setup* can be seen in Figure 4.7. Figures shown here will use the *cabinet-setup* as an example, and the corresponding images for the *box-setup* are presented in Appendix D.

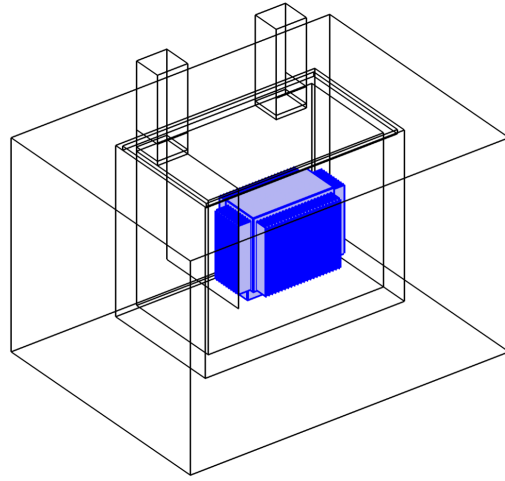
A flow guard was placed parallel to the edge of the inlet (approx. 400 mm) from one of the sides, extending from the top of the housing, down to a distance of 400 mm above the vault's floor highlighted blue in Figure 4.7a. The lid of the vault was modelled as a solid slab of concrete, 50 mm thick, as an approximation for future options (metal lid, brick/concrete lid etc.). The two ventilation geometries defined in section 3.3 (*box/cabinet-setup*), were implemented on top of the lid. These were modelled as two domains, representing only the air inside, and boundaries onto which boundary conditions could be implemented. Ventilation geometries for the gratings were approximated as plane boundaries onto which Grille boundary conditions were applied. Grating geometries were therefore not modelled geometrically.

The transformer was implemented as a simplified geometry. Insulators and *minor* external structures (such as screws or terminals) were omitted and only the cooling fins, as well as the tank housing were modelled. Once the transformer used in Chapter 5 was known, the model was adjusted to meet these dimensions. The transformer's domain and model are shown in Figure 4.7b. It is important to note that only the boundaries of the transformer were utilized in the multi-physics simulation, and that the internal volume did not partake, ergo, no meshes were generated for the internal volume of the transformer.

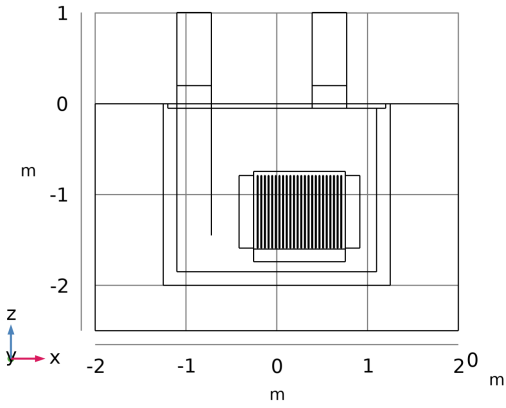
The surrounding soil/earth was also modelled as a solid body, adding 1500 mm of soil around the vault of the substation. 1500 mm were chosen as Zhou et al. had found about 1260 mm of ground matter to participate in thermal effects [16]. The underside of the substation included only 500 mm of soil, to slightly reduce the size of the computational



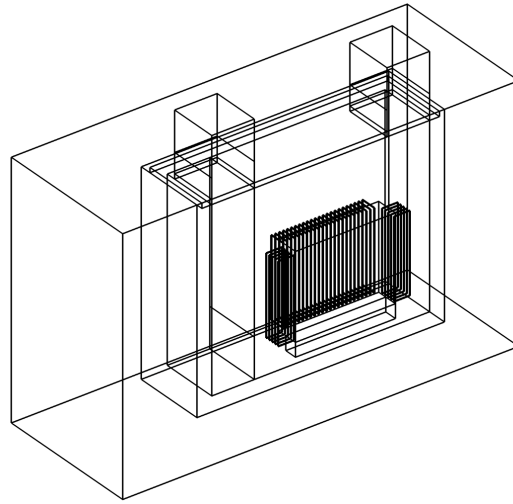
(a) Location of the flow guard in the domain



(b) Simplified transformer



(c) Side view



(d) Half-Box Domain

Figure 4.7.: Different features of the 3D models in COMSOL

domain. Furthermore radiation from the underside of the transformer is minimal, and incoming air would also be at ambient temperature at the bottom.

Finally, as the *box-setup* showed a symmetry plane along the central z - x plane of the geometry, it was halved along this plane, to reduce the computational domains volume, shown in Figure 4.7d.

4.3.1. Boundary Conditions

To model the physics present in the substations heat and mass transfer the following physics models were used in COMSOL: surface-to-surface radiation, heat transfer in solids and fluids, and turbulent flow. Linked via the multi-physics nodes: nonisothermal flow and heat transfer with surface-to-surface radiation. Full explanations of these, and

the detailed equations solved can be found in the reference manuals [59, 60, 64] Using these the following materials and boundary conditions were assigned.

Materials

COMSOL's default Air material was assigned to parts of the domain representing air inside the substation, see Figure 4.8a, this material corresponds to the temperature and pressure dependent properties of air. A concrete material with a fixed thermal conductivity of 1.8 W/(m K) , a thermal capacity of 880 J/(kg K) and density of 2300 kg/m^3 was assigned to the concrete vault and lid of the substation, Figure 4.8b³. It was chosen to model the earth as partially moist sand, with a thermal conductivity of 1.33 W/(m K) , a thermal capacity of 753 J/(kg K) and a density of 2700 kg/m^3 [65], assignment shown in Figure 4.8c. This material can be seen as representative for common ground types in many locations within the Netherlands and Liander's distribution grid, and is used internally as the default ground material for thermal calculations. Foregoing a large discussion about thermal properties of ground, it can be mentioned that this material can be adjusted to meet the requirements of different locations within the distribution grid, in respects to moisture/groundwater levels (resulting in improved thermal properties), and different ground types such as clay, sand or peat [65]. For the flow guard an acrylic material was chosen with a thermal conductivity of 0.18 W/(m K) , thermal capacity of 1470 J/(kg K) and a density of 1190 kg/m^3 , see Figure 4.7a⁴.

Symmetry

A symmetry boundary condition was applied to boundaries along the central z-x plane of the geometry for the *box setup*, see Figure 4.8d.

Heat Transfer

Heat transfer of the vault was modelled utilizing the *surface-to-surface radiation* (S2S radiation) module linked to the *heat transfer in solids and fluids* module via a *heat transfer with surface-to-surface radiation* multi-physics node. This link provided the temperatures and opacities for calculating radiative heat transfer from the heat transfer in solids and fluids interface, from which the radiative energy transfer can be calculated, and returned as heat fluxes on the corresponding boundaries to the heat transfer module. The computational domain encompassed all geometries, except the volume of the transformer, of which only the boundaries were included (also resulting in no mesh generation inside the transformer's volume, but only on its surface).

³Material from COMSOL's material database.

⁴Material from COMSOL's material database.

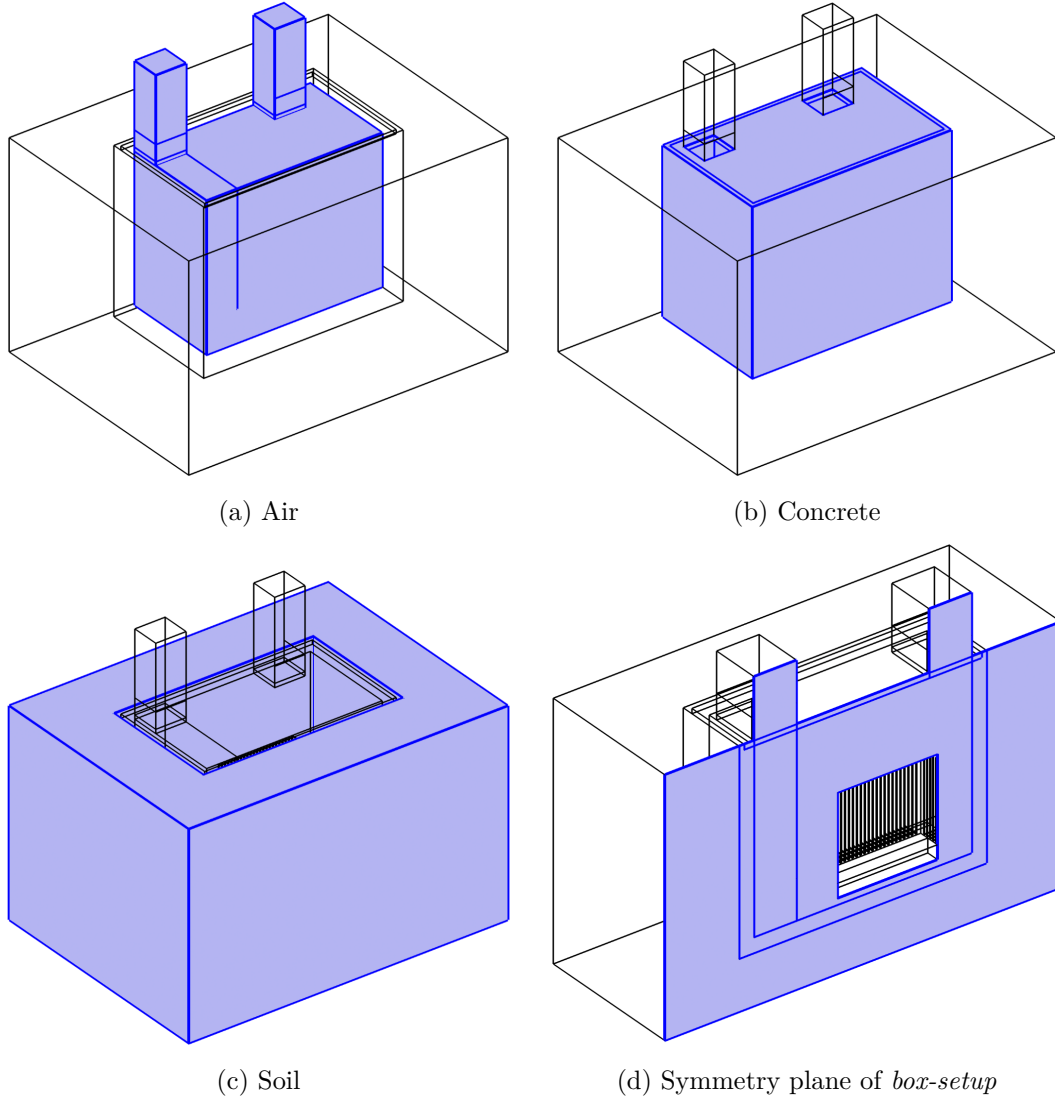


Figure 4.8.: Material assignments and symmetry plane in COMSOL

Heat Transfer - Radiation

The domain for solving radiative heat transfer was limited to the inside portion of the vault. All boundaries participating in S2S radiation were assumed to be diffuse surfaces, with an emissivity $\varepsilon = 0.85$ for the concrete walls, and $\varepsilon = 0.9$ for the painted surface of the transformer [66]. The outer boundaries of the domain correspond to the walls on the inside faces of the vault's housing, shown in Figure 4.9a. The air domain inside the substation was treated as a transparent medium, not participating in the heat transfer. While the transformer's main housing (without the fins) was treated as an opaque domain. A simplification of the transformer was implemented as follows: fins were not modelled as radiative boundaries, but instead as transparent, and not participating in radiative heat transfer. Instead it was chosen to let only the main housing of the transformer emit radiation, such that the outer walls of the transformer's main housing

(minus the fins) represent the emitting diffuse surfaces, see Figure 4.9b. Furthermore the flow guard was simplified and modelled as transparent, therefore not participating in the radiative heat transfer. Ambient radiation (e.g. from the sun) was not modelled in this work.

Heat Transfer - Solid and Fluids

The heat transfer in solids and fluids domains were split into two main components. The solid portion encompassed the solid materials, such as the concrete and soil (Figure 4.8b, 4.8c). While the fluid portion of the domain included the air within the substation, Figure 4.8a. Only the transformer's boundaries were included in the computational domain. The reference temperature, as well as the initial temperature was set to the parametrically defined ambient temperature T_{amb} (22.6 °C for the *cabinet-setup*, 23 °C for the *box-setup*). Boundaries of the solid domains (concrete and soil), in contact with ambient, were modelled with a temperature boundary condition of T_{amb} , Figure 4.9c. As testing was performed above ground a constant ambient temperature was used for both air, and the ground. For underground transformers deployed in the field, a lower ground temperature needs to be taken into consideration. While the boundaries of the transformer were assigned a temperature gradient ranging from $T_{\text{top}} = 86$ °C to $T_{\text{bottom}} = 52$ °C, Figure 4.9d. In these preliminary simulations this temperature gradient was based on old measurement results⁵, and was only used to check model convergence.

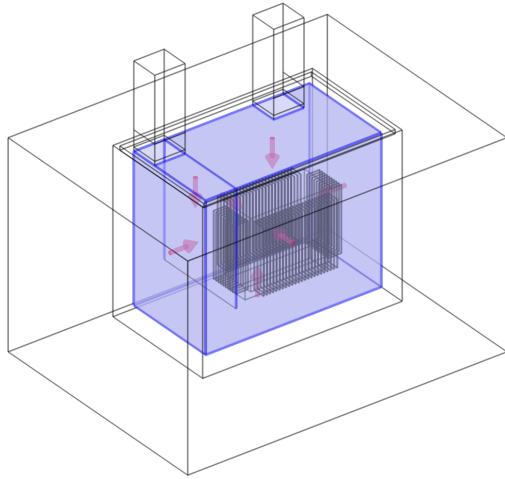
The inlet was assigned an *Inflow* boundary condition assuming an upstream temperature of T_{amb} , while the outflow boundaries were assigned with an *Outflow* boundary condition. The boundaries can be seen in Figure 4.9e, 4.9f. To simplify the model, boundaries of the ventilation geometries representing walls and facing ambient air were treated as thermal insulation, see Figure 4.10.

The flow guard was implemented as a *Thin Layer* with the *Thermally thick* approximation, with a thickness of 18 mm, shown in Figure 4.7a.

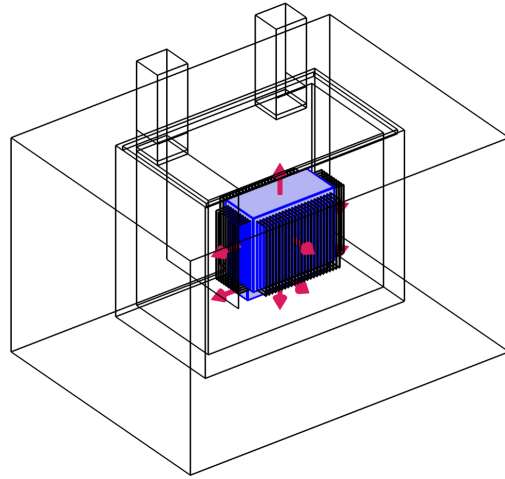
Flow Domain

The flow domain for simulating turbulent flow encompasses the cooling in-/outlets, as well as the air volume inside the substation, see *Air* assignment in Figure 4.8a. The flow regime was set to an incompressible turbulent flow and gravity, with a low Reynolds approach and automatic wall treatment based on work by Ramos et al. in [13]. The reference pressure was set to 1 atm. Wall conditions were assumed as no slip on external walls, and the internal wall of the flow guard. Ventilation grilles were modelled as a

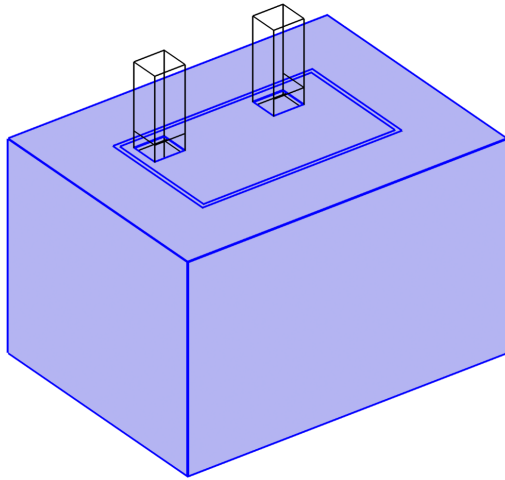
⁵Thermal test by Liander of a 630 kVA transformer in a compact substation



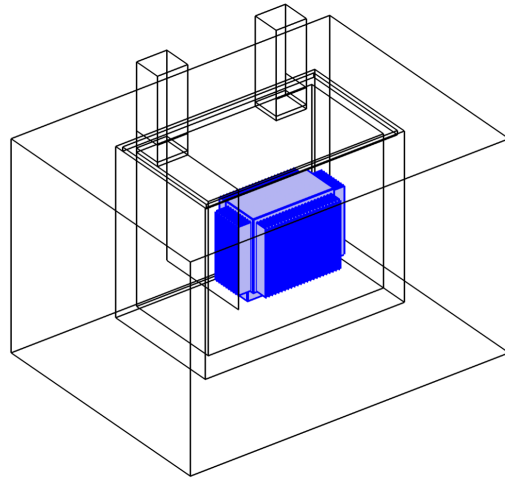
(a) Radiating walls of the vault



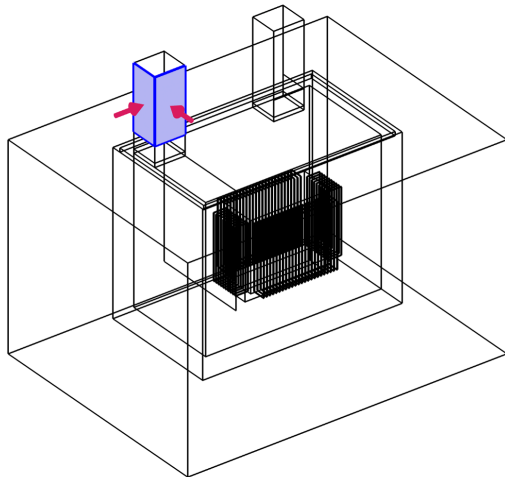
(b) Radiation boundaries on the transformer



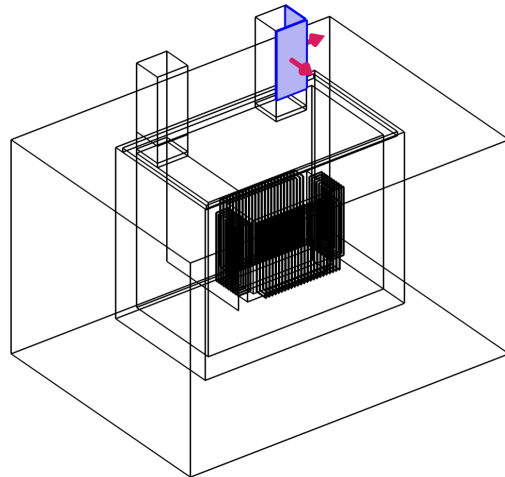
(c) Ambient Temperature



(d) Transformer temperature



(e) (Grille-)Inlet



(f) (Grille-)Outlet

Figure 4.9.: Radiative (a-b) and thermal (c-f) boundaries assigned to the *cabinet-setup*

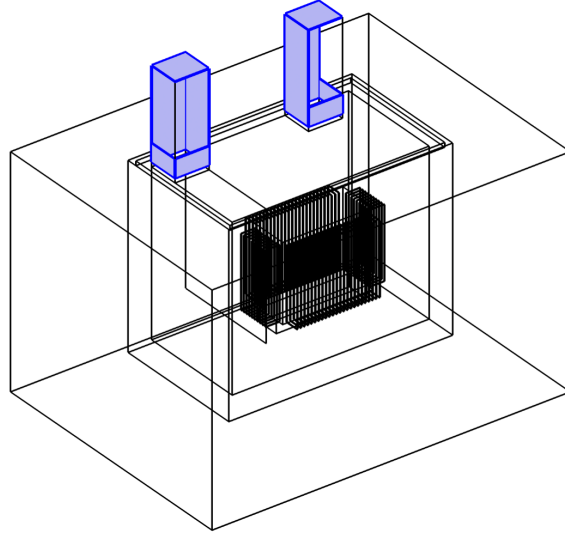


Figure 4.10.: Thermal insulation boundaries on the cabinet setup.

Grille boundary condition, with a dimensionless loss coefficient $K = 80$ for the *box-setup* and $K = 25$ in the *cabinet-setup* [33, 59, 67]. These K values corresponded to the grilles available for testing in Chapter 5. The input/exit pressure was set to 0 Pa (ambient pressure). Turbulent intensity on the inlet was assumed as medium. The boundaries were the same as for the in-/outlets of the thermal domain, shown in Figure 4.9e, 4.9f.

Nonisothermal Flow

To link the heat transfer and fluid flow interfaces a *Nonisothermal Flow* multi-physics node was added. Under this the Boussinesq approximation was applied again to save on computation times, and provide density variations for the gravitational term in the flow domain. Both the density and reference temperature were specified from the heat transfer interface ($T_{\text{ref}} = T_{\text{amb}}$).

4.4. Preliminary Results and Discussion

Preliminary results of the two models, with the estimated values for the power loss in the *fin-slice* model and estimated transformer temperatures in the vault models are presented below.

4.4.1. Fin-Slice Model

The fin model was simulated with the estimated power losses shown in Table 4.1. The simulation was run in two steps. The first step was a *wall distance initialization* to

calculate wall distances of the mesh. The second step consisted of a time dependent solver, with a simulated time from zero to nine hours, after which the simulation could be considered steady state. The step size was set to automatic, with an initial maximum step size of 1e-6 s, which was necessary to achieve convergence as the flow developed from rest. All other settings were left at the default settings suggested by COMSOL. The domains initial temperatures were set to $T_{amb} = 18^\circ\text{C}$. An automatically generated *Extremely coarse* mesh was used.

Select preliminary results, with plots based on those presented by Gastelurrutia et al. in [55], for a qualitative comparison, are shown in Figure 4.11. Figure 4.11a shows the temperature distribution of the fluid domain, at a plane in the centre of the *fin-slice* models y-axis ($y = 20\text{ mm}$). A temperature gradient from the top to the bottom of the model can be observed, with the hottest parts of the oil near the upper part of the windings. In general this figure is comparable to those in Figure 7. in [55], although the temperature gradient seems more gradual across the whole fin in the results presented here.

The fins surface temperature distribution is shown in Figure 4.11b, with similar distributions to those in [55]. Akin to the calculations by Gastelurrutia et al., the hottest part of the surface is where the top of the fin connects to the main housing of the transformer.

Flow patterns are shown in Figure 4.11c and 4.11d. General flow patterns of the geometry presented in this work are similar to those shown in [55], but some minor differences arise. Similarities can be seen in the *1st and 2nd suction regions* (according to Gastelurrutia et al.), where the oil gets sucked out of the fin at the top, and bottom of the windings. However, some minor differences can also be seen. Such as the existence of a much larger circulation of hot oil in the upper part of the *fin-slice* model here, compared to the one presented in [55].

The surface temperature along the outer centreline, shown in Figure 4.12, of the *fin-slice* model was plotted for later comparison with measured surface temperatures, and can be seen in Figure 4.13. Here it can again be seen that the hottest part on the outside of the fin is at a z-height of approximately 0.96 m, or an arc length between 1.2-1.4 m, corresponding to the upper part of the fin, and where it attaches to the body of the transformer. Furthermore it can be observed that the lid is actually colder than the top of the fin, and that the underside of the transformer only shows minor variations in temperature.

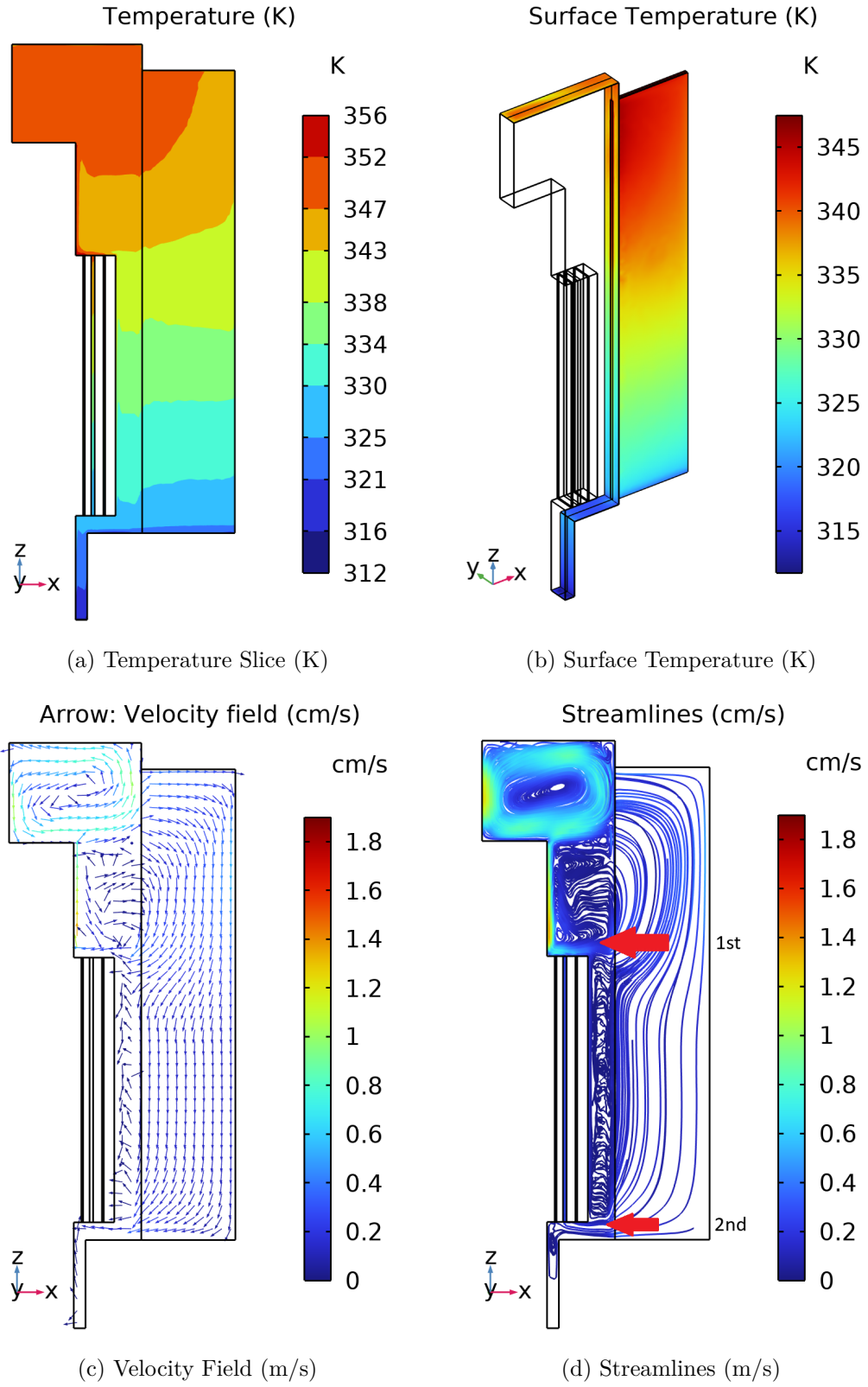


Figure 4.11.: Plots of the preliminary *fin-slice* simulation. (a-c) based on Gastelurrutia et al. in [55]

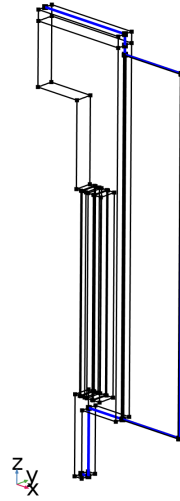


Figure 4.12.: Boundary lines from which the outside temperature profile was recorded.

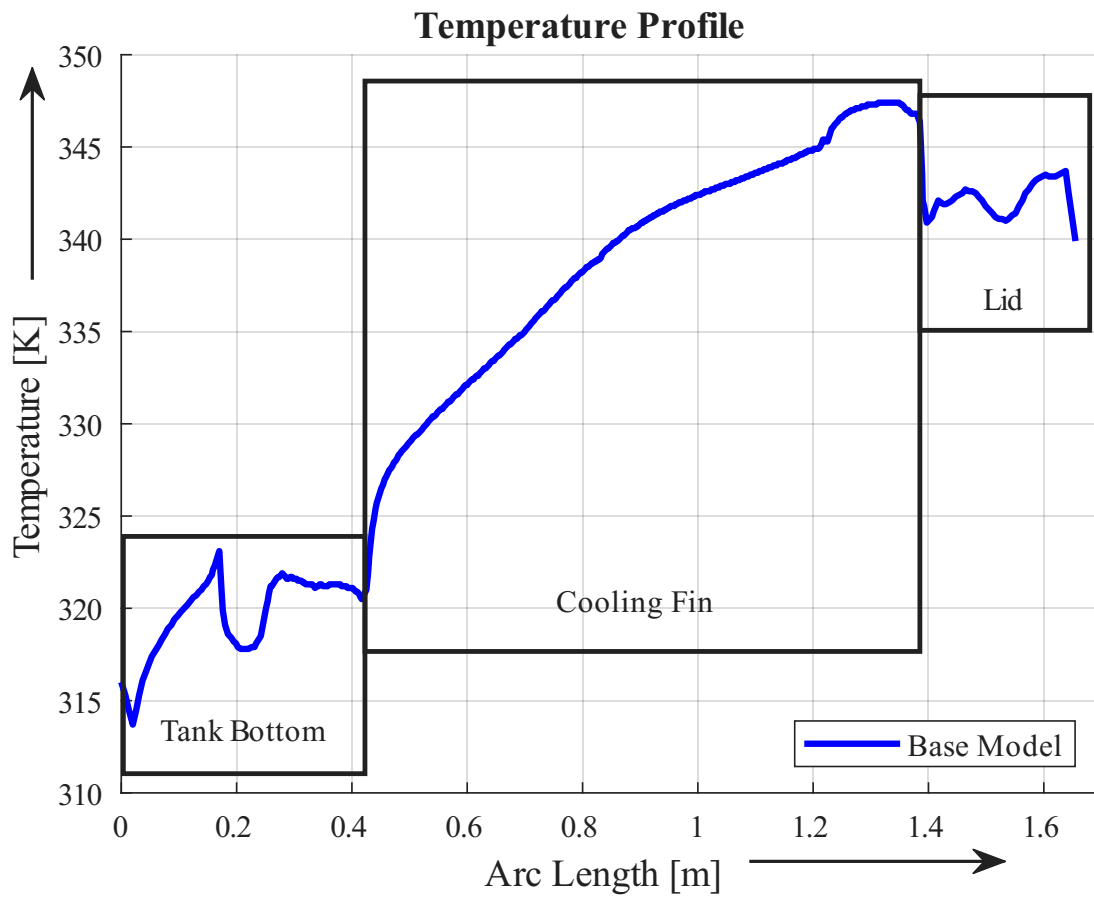


Figure 4.13.: Temperature profile of the transformer along the arc length. Key regions are labelled in the boxes. Zero arc length corresponds to the bottom of the *fin-slice* model.

4.4.2. Vault Models

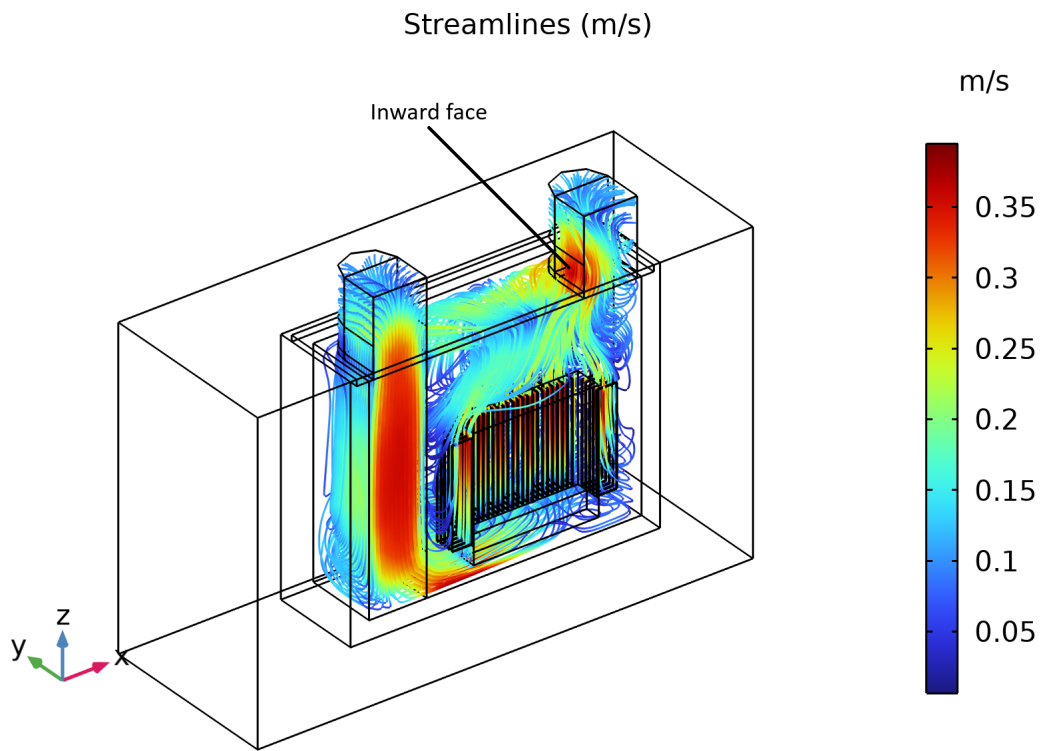
A preliminary geometry of the *box-setup* was simulated to test convergence. Simulations were ran with a incompressible, low Reynolds flow regime, and assumed to be converged when residual errors were bellow $1e-4$. Select results are displayed in Figures 4.14 through 4.16. Assumed ambient temperature T_{amb} was 18°C .

The plots of streamlines in Figures 4.14 show the formation of a chimney effect, as the air being drawn down is channelled by the flow guard. Mixing of the air takes place, and recirculation arrives at the top, as well as possibilities for recirculation in the downstream section. Hot air rises as a plume, and is then evacuated through the outlet, though the highest flow velocities there can be observed on the *inward* facing side. Streamlines seem to indicate that air travels along the bottom of the vault, reaching most parts of the transformer. However the far section (under the outlet) shows lower flow velocities, compared to the section closer to the inlet.

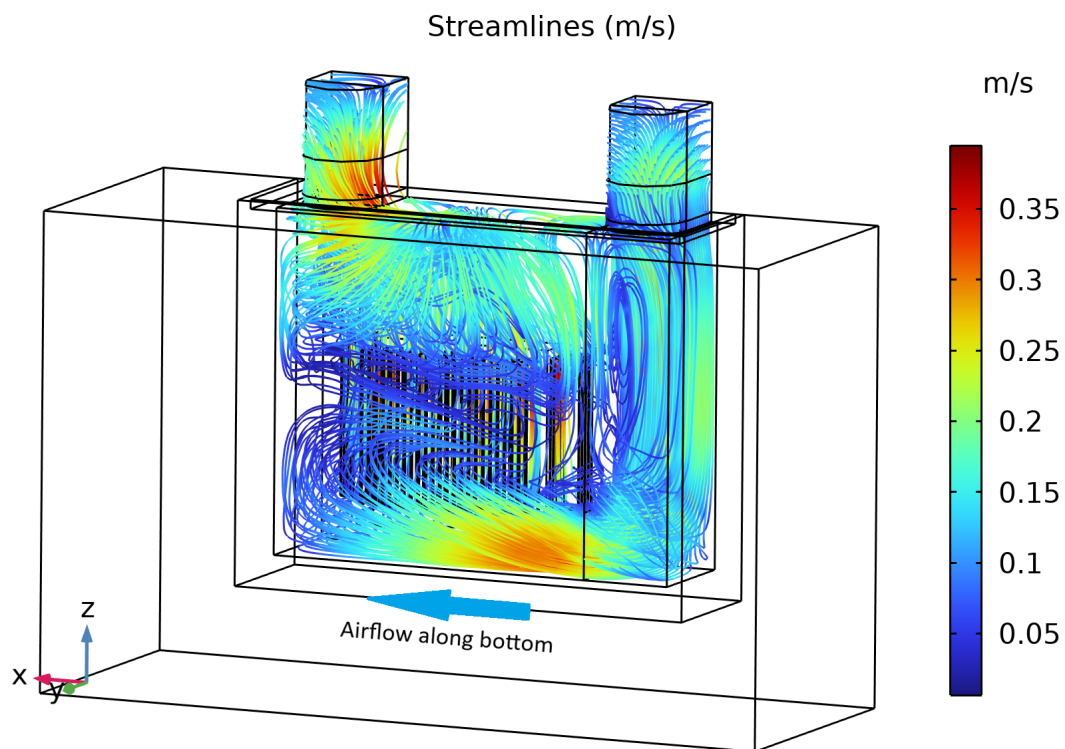
Similar observations can be seen in the velocity field, plotted in Figure 4.15a. With recirculation visible in the left corner of the transformer's section. While the general flow direction goes towards the outlet. Flow velocities are highest on the inlet section between the vault wall and the flow guard, as well as on rising air between the fins of the transformer, and inner side of the outlet vent. Flow velocities in general are of similar magnitude (0 - 1 m/s) to those presented by Ramos et al. in [13].

Figure 4.15b shows the temperature distribution along the symmetry plane. A split, at roughly half height of the transformer between cooler incoming air, and warm air from the transformer is visible. Showing that the cool incoming air rises through the transformer, warms up, and collects at the top. Ground temperatures are slightly elevated, but fall within expected results (300- 305 K) form [16].

Finally Figures 4.16 shows the imposed thermal boundary condition of the transformer, in this step still based on results of previous thermal studies of similar distribution transformers by Liander.

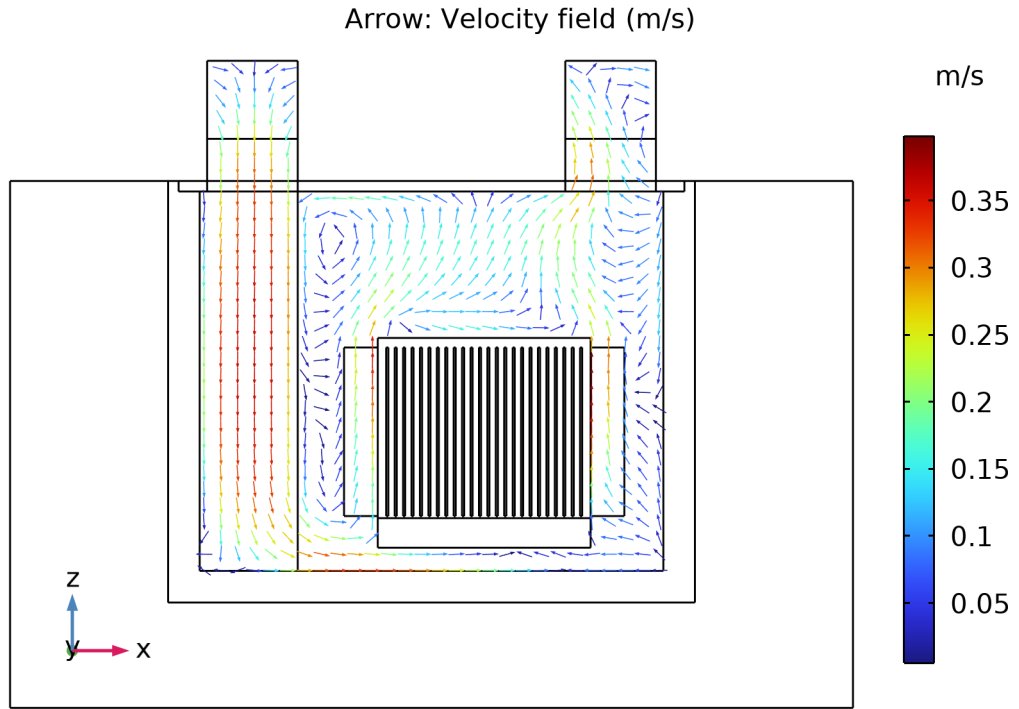


(a) Streamlines (m/s), frontal view

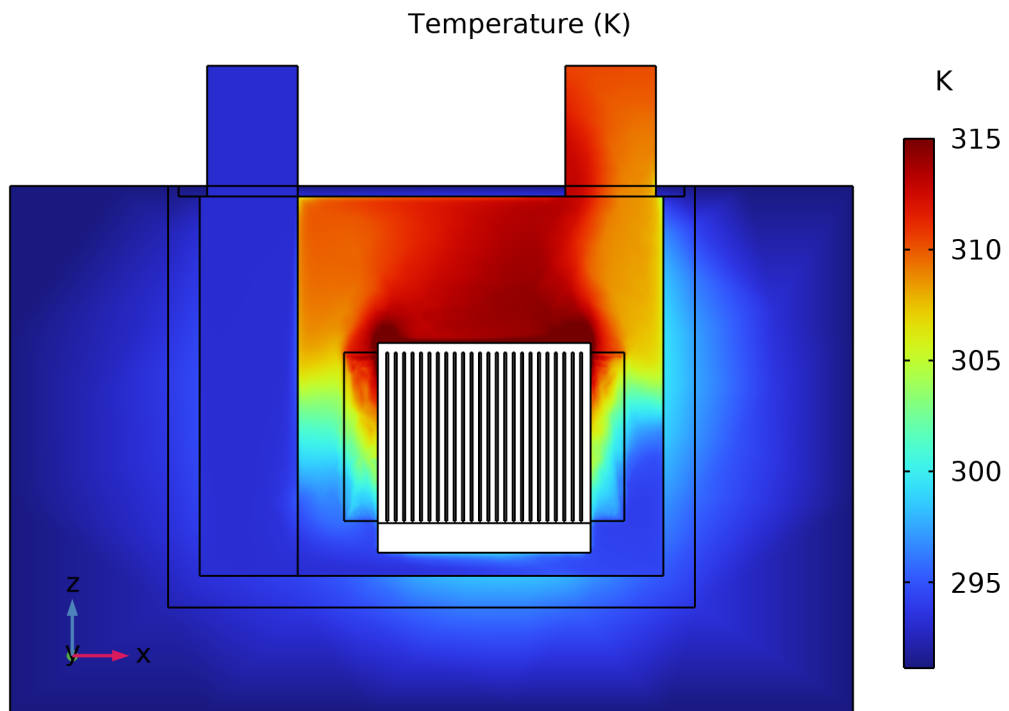


(b) Streamlines (m/s), rear view

Figure 4.14.: Streamlines, coloured by velocity magnitude (m/s) of the preliminary simulation.



(a) Velocity field (m/s)



(b) Temperature Distribution (K)

Figure 4.15.: Velocity field and temperature distribution of the preliminary *box-setup*. Values plotted at the symmetry plane.

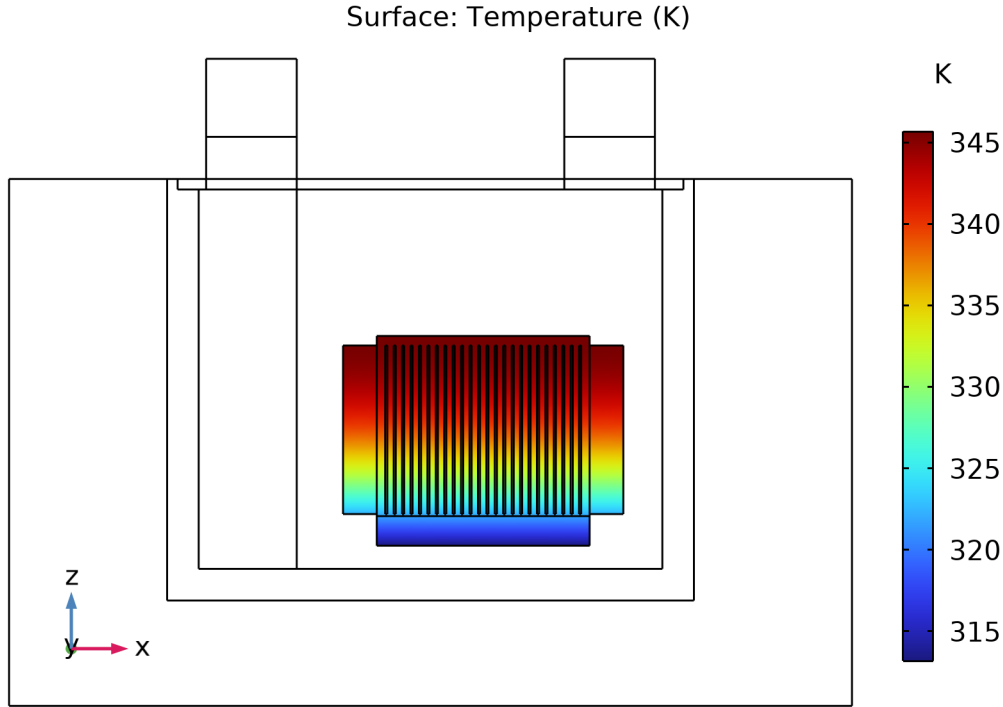


Figure 4.16.: Imposed transformer boundary temperature (K)

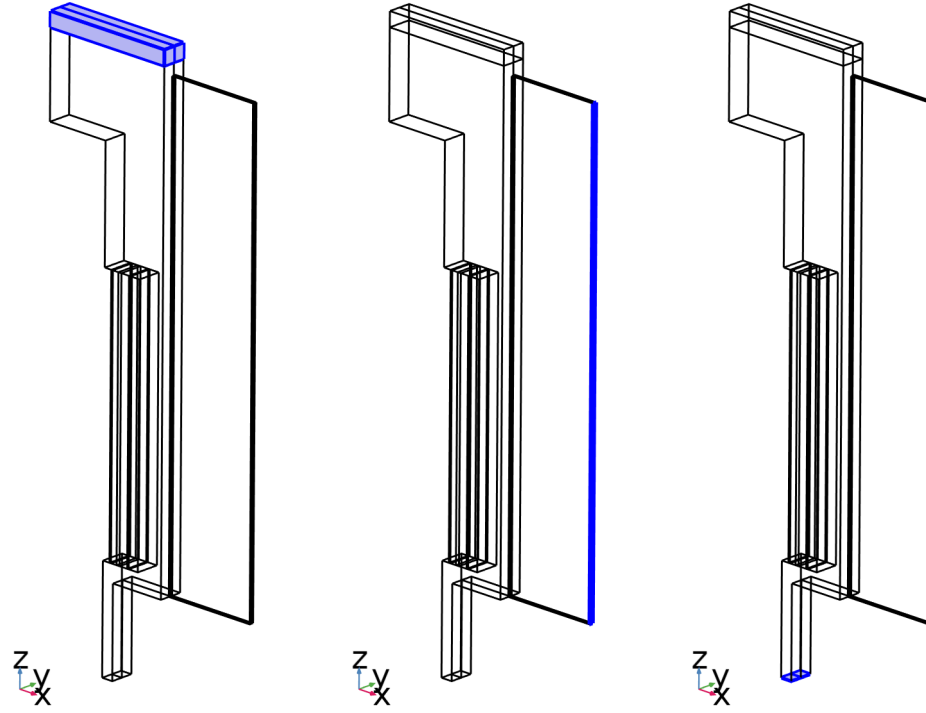
4.5. Mesh Refinement Study

To analyse the impact of the mesh resolution in the computational domain a mesh refinement study was conducted for the *fin-slice* model, and the *box-setup* model.

4.5.1. Fin Model

A total of six different meshes were tested. Meshing was performed using the automatic mesh generation of COMSOL, ranging from *Extremely Coarse* to *Normal* for five meshes. One mesh was based on an *Extra Coarse* mesh, and refined manually in critical areas for heat transfer: the cooling channels and the fin. At their base all meshes consist of different elements, such as tetrahedral, hexahedral, prisms or pyramids. A key feature in the meshes generated for the fin model are the *boundary layer* elements on walls. These provide a high degree of mesh refinement in wall regions, to better capture the wall effects of the flow. The impact of mesh resolution was analysed for key thermal values, such as the top-oil temperature (Fig. 4.17a), maximum fin front temperature (Fig. 4.17b), and the minimum temperature of the outer walls (Fig. 4.17c). A comparison of the fins outer temperature profile (Fig. 4.12) was also made.

Table 4.2 provides an overview of the meshes analysed. Figures and details of the generated meshes can be seen in Appendix E. The coarsest mesh generated consisted



(a) Average Top Oil Probe (b) $T_{\max}$ -Probe Fin Front (c) $T_{\min}$ -Probe Bottom

Figure 4.17.: Location of the average top-oil, maximum and minimum temperature probes on the *fin-slice* model.

of 101,007 elements, with a solving time of 5 h 30 min. While the most detailed mesh consisted of 1,439,582 elements and took 47 h and 24 minutes to solve. While it was initially hoped that the manual mesh refinement would provide shorter solving times in areas with predictable flow, this refinement turned out to be counter productive, drastically increasing solving times, relative to the number of elements, up to above 42 h.

Table 4.2.: Studied Meshes *Fin-Slice* model

Mesh Settings	Nr. Elements	Sol. Time [hh:mm:ss]
Extremely Coarse	101,007	5:30:58
Extra Coarse	174,651	6:38:30
Manual	213,726	42:30:58
Coarser	402,665	8:33:43
Coarse	756,670	16:34:55
Normal	1,439,582	47:24:08

Figure 4.18 shows the values of the defined temperature probes compared to the number of elements. Probes in the upper region of the fin, top-oil and maximum fin front, show little change with mesh resolution. The minimum temperature at the bottom of the fin

decreases from 312.4 K to 308.5 K as mesh resolution increases.

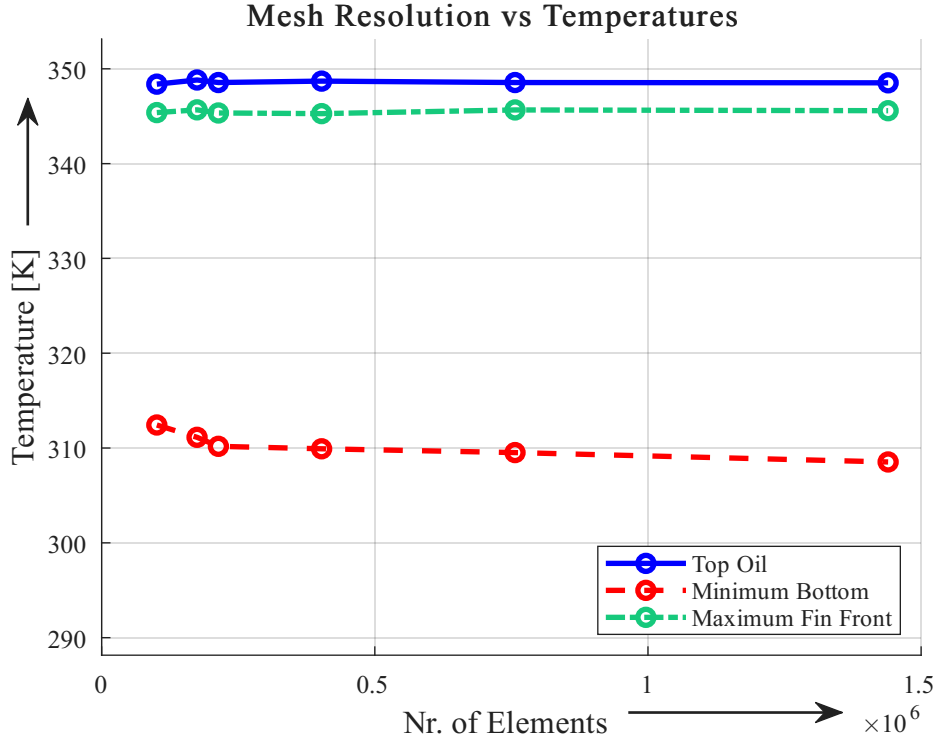


Figure 4.18.: Impact of mesh refinement on the different thermal regions.

Figures 4.19 shows the temperature profile along the arc length on the outside profile of the fin. Once again differences can be observed in the lower region of the fin as the mesh is refined. Variations along the front of the fin (0.4 m to 0.945 m in the arc length) show little differences in temperature with increased mesh refinement, except for the manually refined mesh, which is approx. 0.5 to 0.8 K lower. Large fluctuations can be seen in the upper region of the fin. These are probably due to the different stable flow patterns that can form in the upper area of the model, see Figures 4.20. These fluctuations are however local, and not visible when taking average temperatures across the *lid* boundary, or the top-oil temperature.

As little variation in top-oil temperature was visible in finer meshes it was chosen to utilize the *Extremely Coarse* mesh, and its shorter solving time for testing purposes e.g. in model variations. While the *Coarse* mesh can later be used to accurately simulate the fin temperatures for specific designs.

4.5.2. Vault Model

The effects of mesh refinement for the vault model were studied for the *box-setup*. Simulations were solved as steady state, under the *low Reynolds* flow regime. Convergence was assumed to be achieved when the algebraic residual error of the non-isothermal flow

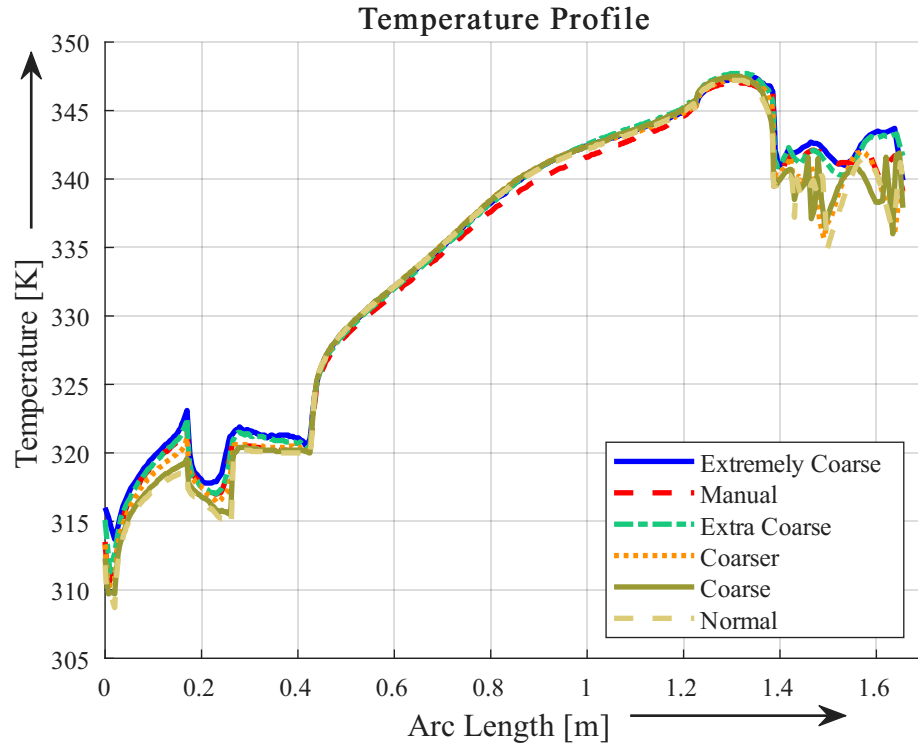
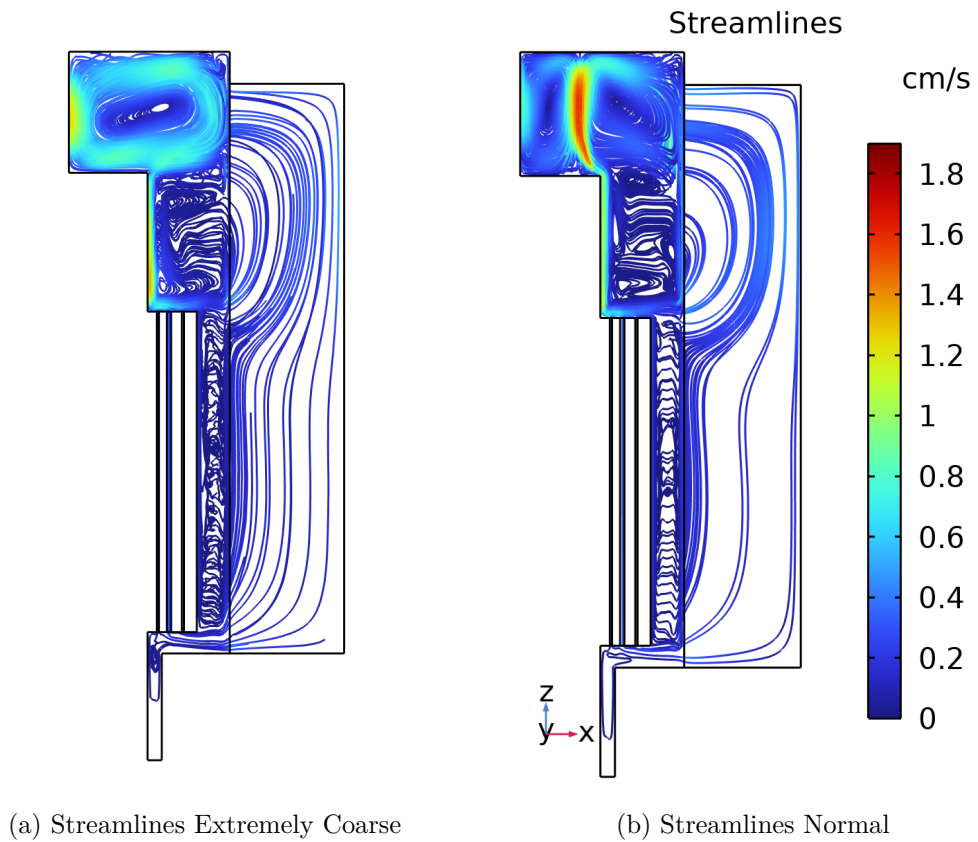


Figure 4.19.: Temperature profile arc length.



(a) Streamlines Extremely Coarse

(b) Streamlines Normal

Figure 4.20.: Streamlines of the extremely coarse and normal mesh.

and turbulence variables was below $1e-4$. Three meshes were simulated, the smallest one at approx. 128,000 elements and the largest at approx. 762,000, shown in Table 4.3. A more detailed mesh of, e.g. *normal*, resolution could not be studied due to time calculation time constraints. The average air temperature inside the compartment, average temperature on the inside of the walls and lid, as well as the in-/outlet average velocity magnitudes were used for comparison. The thermal variables were chosen, as these will be used in the linked model in section 4.6. Cross sections of the meshes used can be seen in Appendix E.

Table 4.3.: Studied Meshes *Box-setup* Model

Mesh Settings	Nr. Elements	Sol. Time [hh:mm]
Extremely Coarse	127,642	22:55
Coarser	352,413	59:06
Coarse	761,663	85:41

Figures 4.21 and 4.22 show the changes in the tracked variables with increasing mesh resolution. Temperatures gradually decrease with increasing mesh resolution. The largest difference is visible in the average temperature of the lid, decreasing by approx. 3 K.

Little change can be observed in the average in- and outlet velocities. Although when observing the velocity magnitude profile along the plane of symmetry in Figure 4.23, differences can be seen in locations of high flow speeds, such as in the flow guard region, the fins, and the inner edge of the outlet. To help with design finding of the validated model in Chapter 6, it was therefore chosen to allow for rough simulations with the *extremely coarse* mesh settings, and apply the *coarse* mesh when resulting design improvements need to be studied in detail.

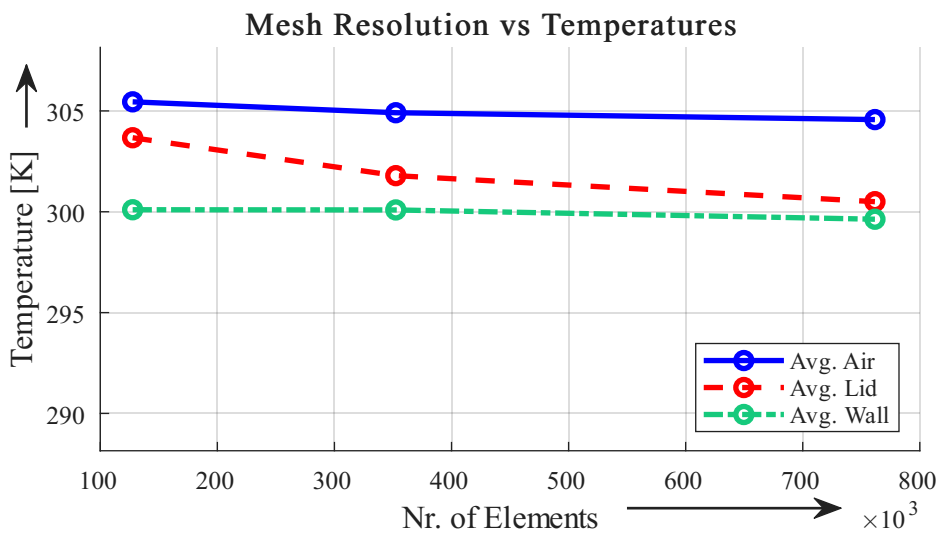


Figure 4.21.: Thermal variables

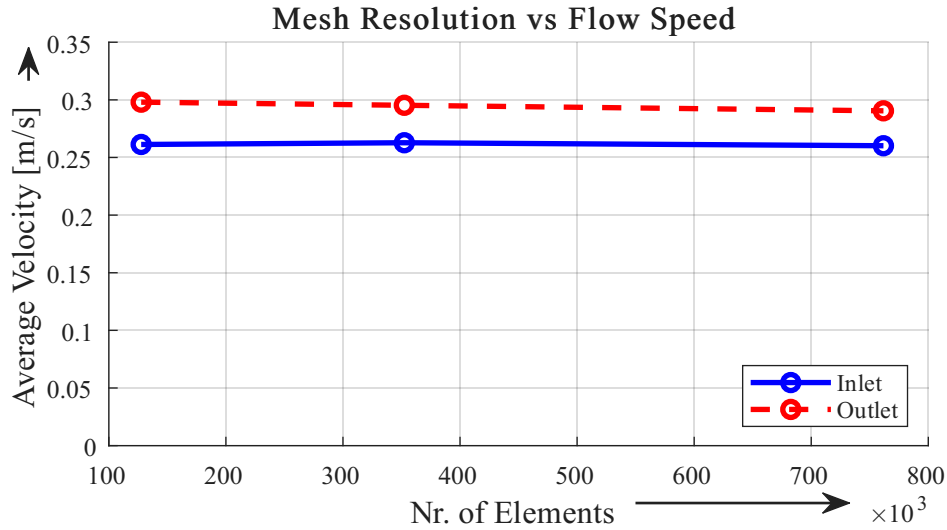


Figure 4.22.: Average in-/outlet velocities

4.6. The Linked Model

Now that the separate component models were defined, a link between the two was needed. The *fin-slice* model and vault models were implemented as two separate components, within the same solver structure. In the separate forms, both models assumed constant ambient temperatures of T_{amb} , and the vault model assumed a constant temperature distribution across the transformer. While a constant ambient temperature for the vault is an acceptable approximation, especially in a large testing laboratory, the transformer fin boundary conditions will see greatly different ambient conditions when placed inside a vault (higher ambient air temperatures, or wall temperatures for radiation). Furthermore, the temperature gradient of the transformer in the vault, must be based on that of the actual temperatures reached by the *fin-slice* model, to reflect changes in thermal output, which is the source of natural convection.

There are different methods, of varying complexity, available to achieving these links within COMSOL. In this work it was chosen to utilize boundary and domain probes, representing characteristic values, for instance the average wall temperature, and linking these to boundary conditions in the respective components.

4.6.1. Links given to the Fin-Slice Model

To represent changes in ambient conditions inside the vault, three temperature probes were defined inside the vault's domain, which were then handed to thermal boundary conditions of the *fin-slice* model. Changes in ambient air temperature were represented by a domain probe for the average air temperature inside the vault and the inlet ventilation geometry, $T_{\text{avg_air}}$. This variable was then assigned as the external temperature in all

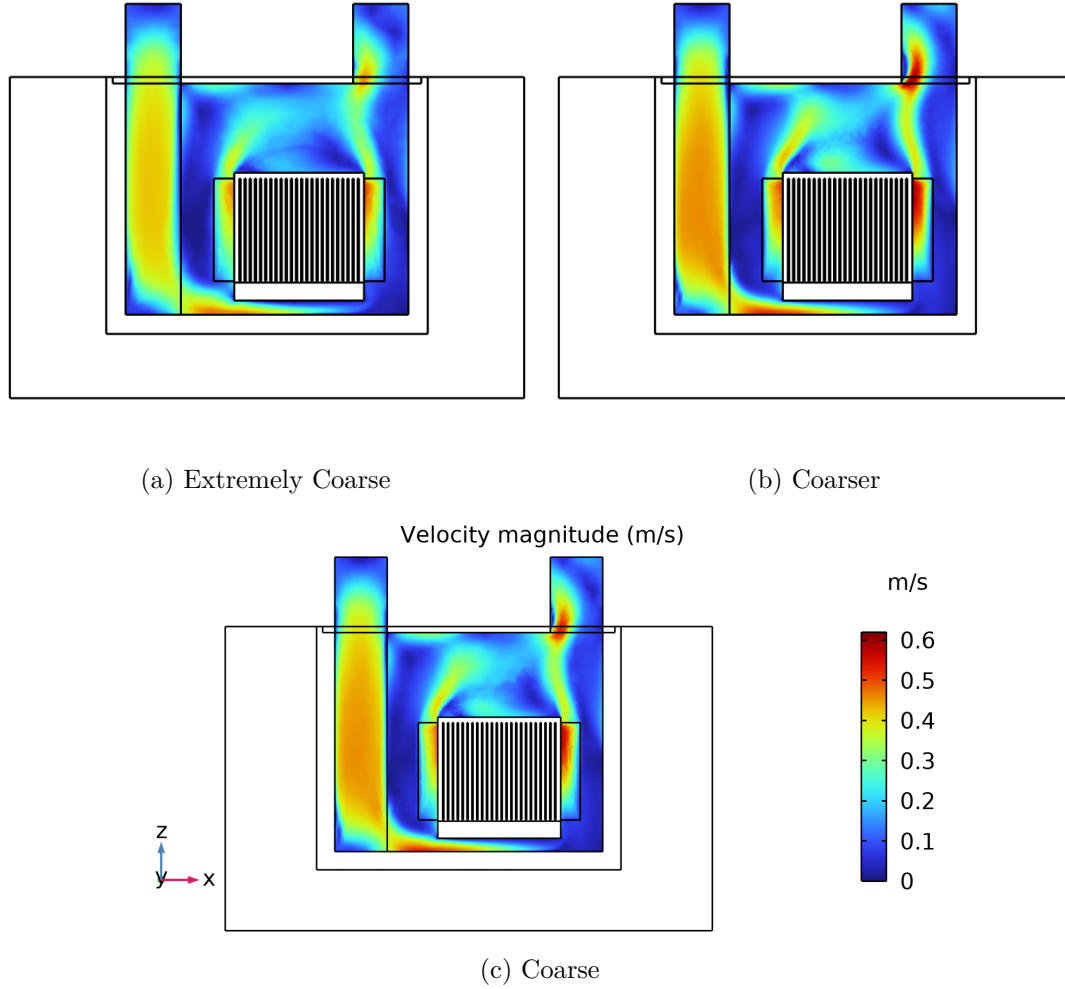


Figure 4.23.: Velocity magnitude (m/s) plotted across the plane of symmetry in the *box-setup*.

convective boundary conditions (see Fig. 4.5) of the *fin-slice* such that $T_{\text{ext}} = T_{\text{avg_air}}$. As the vertical sides of the transformer would be directly facing the adjacent walls of the vault, the second defined probe was that of the average wall temperature $T_{\text{avg_wall}}$. This temperature was then assigned as an ambient temperature to vertical radiative boundaries of the *fin-slice* model. Finally, the average lid temperature $T_{\text{avg_lid}}$ was probed, and assigned to radiative boundaries on the *fin-slice* model facing in the positive z -direction (see vertical and horizontal blue areas in Fig. 4.5f). The defined probes in the vault, and their respective domains and boundaries can be seen in Figure 4.24b.

4.6.2. Transformer Temperature Profile in the Vault Model

As the temperature distribution on the outside of a transformer is not linear, a thermal gradient, in the form of a temperature function $T(z)$ had to be applied to the outside of

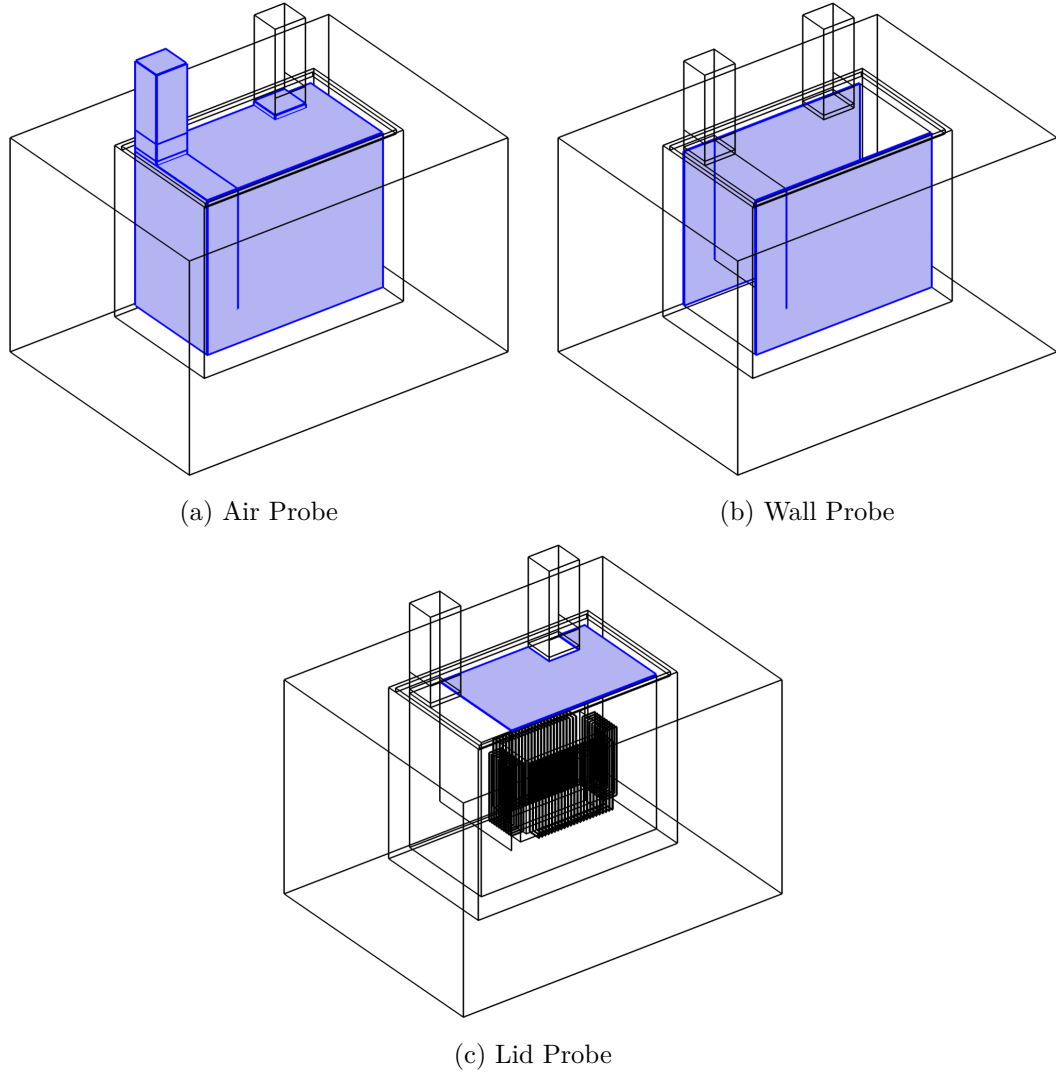


Figure 4.24.: Temperature probe domains and boundaries of the vault model, passed to the *fin-slice* model. Temperatures were taken as average.

the transformer in the vault model. While multiple different methods exist, it was chosen to define a 1st and 2nd degree polynomial, which could both be calculated and defined within COMSOL by supplying two probe temperatures: a maximum, and minimum. As the first order function showed a bad fit, the derivation will not be discussed, it is however included in the graph for illustrative purposes.

For the temperature distribution of the second degree, it was assumed that the maximum of the curve was at $z = h_{\text{Transf.}} = 0.995$ m. This way three known points were provided, which allows for the solving of the 2nd order function:

$$T_{2\text{nd}}(z) = az^2 + bz + c \quad (4.16)$$

Assuming a maximum temperature (T_{max}) at the apex and $z = h$ m, and a minimum

$T_{\min}$ at $z = 0$ m we can solve for a , b and c .

$$T_{2\text{nd}}(0) = a \cdot 0^2 + b \cdot 0 + c = T_{\min} \quad (4.17)$$

$$c = T_{\min} \quad (4.18)$$

as the gradient of $T_{2\text{nd}}(z)$ is 0 at $z = h_{\text{Transf.}} = 0.995$ m we get:

$$\frac{dT_{2\text{nd}}(z)}{dz} = 2az + b \quad (4.19)$$

$$\left. \frac{dT_{2\text{nd}}(z)}{dz} \right|_{z=h_{\text{Transf.}}} = 0 = 2ah_{\text{Transf.}} + b \quad (4.20)$$

Resulting in:

$$b = -2ah_{\text{Transf.}} \quad (4.21)$$

Finally solving for a , using $T_{2\text{nd}}(h_{\text{Transf.}}) = T_{\max}$:

$$T_{\max} = ah_{\text{Transf.}}^2 - 2ah \cdot h_{\text{Transf.}} + T_{\min} \quad (4.22)$$

$$T_{\max} - T_{\min} = a(h_{\text{Transf.}}^2 - 2h_{\text{Transf.}}^2) \quad (4.23)$$

$$a = \frac{T_{\max} - T_{\min}}{-h_{\text{Transf.}}^2} \quad (4.24)$$

These two fits were then evaluated in MATLAB 2025a and compared to each other, as well as a MATLAB 2nd-order fit using the `fit()` function. The resulting temperature profiles can be seen in Figure 4.25. The solid black line represents the simulated temperature profile along the line shown in 4.12, and the dashed lines represent different fit functions. The ideal 2nd order fit from the MATLAB function shows a normalized root mean squared error (NRMSE) of 0.11, while the 2nd order fit as defined above has a slightly higher NRMSE of 0.15, and that of the first order fit is 0.77. Large deviations, especially in the central section, between the first order fit and the simulated temperature profile can be seen. Applying the 1st order fit to the transformer in the vault model would result in an underestimation of the thermal load, and thereby a reduced ambient temperature. A risk of underestimating the final top-oil temperature therefore exists with the first order fit, and it was chosen to not apply this onto the boundary condition.

The second order fit follows the simulated temperature profile closely, slightly underestimating the temperature in the lower regions, up to $z = 0.4$ m, but overestimating the temperature at the lid. As the error of this fit is much lower than that of the first order fit, and close to the ideal second order fit in MATLAB, it was chosen to apply this function as the boundary condition for the transformer's temperature in the vault model.

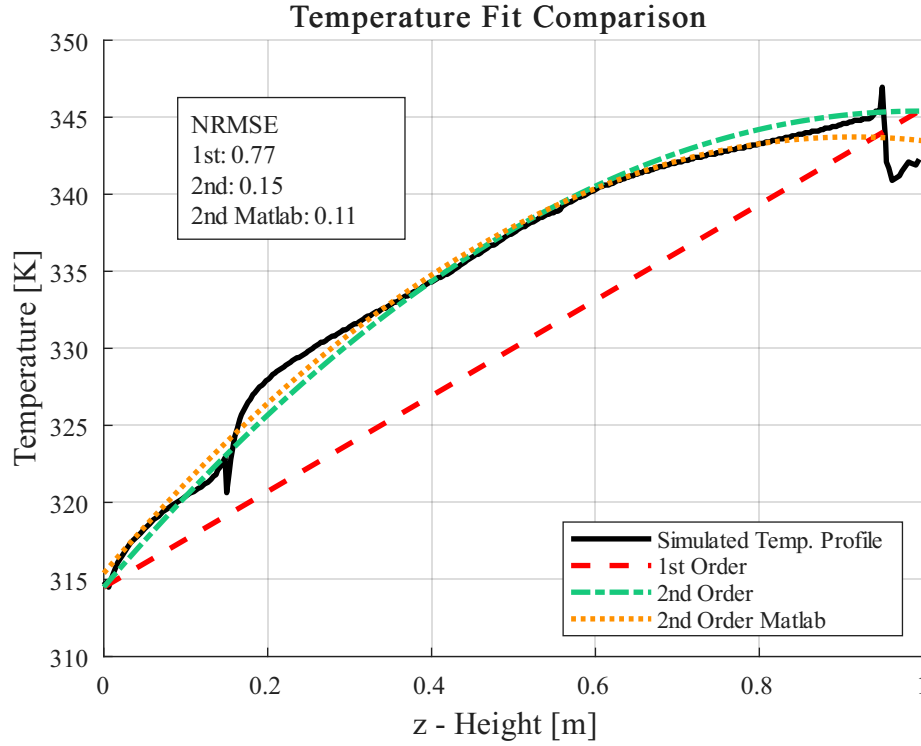


Figure 4.25.: Comparison of fit-functions for the *fin-slice* model

4.7. Preliminary Results Linked Model

Before a lab test was implemented, a feasibility test was performed with the linked model, assuming a *box-setup* for the vault. Power losses were estimated as outlined in Table 4.1. The total in-/outlet area was determined according to equation F.1, and set to 0.8 m^2 . As this equation is designed to estimate the cooling class and needed ventilation area for an indoor substation, it was not yet known if the design would ensure for adequate cooling.

The simulation was solved as a time dependent model, in two steps, with an extremely coarse mesh on the *fin-slice*, and an extra coarse mesh on the vault model. To better initialize and stabilize the solver in the vault model, the vault's flow regime was first set to a standard $k-\varepsilon$ model, and solved for a simulated time of zero to three hours. After which the result was passed to the low Reynolds model described above and solved for a further simulated time of 10 h to ensure thermal equilibrium. Steady state was assumed to be achieved when the temperature change of the top-oil was under 1 K/h . The temperature boundaries for the solid ground domains was set to 18°C , while the inlet air temperatures were set to 20°C . The total computation time for these steps summed up to 50 h, enabling computation over a weekend.

Thermal equilibrium was reached at a time of 18000 s in the low Reynolds step, at which the top-oil temperature reached 95.6°C (a rise over ambient of 75.6°C), with fin

surface temperatures ranging from approximately 47 °C to 92 °C, shown in Fig. 4.26. Comparing the rise of 75.6 °C seen here to the limits of 60 °C, in IEC 60076-2 Tab. 1, we can see that it is exceeded by 15.6 °C. However, taking into account that these temperatures are often tested and certified on free standing transformers, the top-oil temperature reached here would be within a enclosure class of 20, as long as the free standing top-oil temperature rise of the transformer is above 55.6 °C. Validation of this claim will be discussed in Chapter 5 and 6.

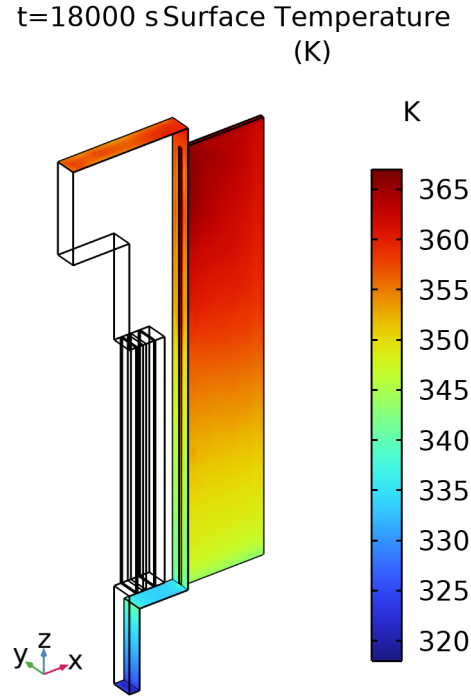


Figure 4.26.: Fin surface temperatures of the preliminary combined simulation.

Figure 4.27 shows a cross section through the central plane of the vault model, with temperatures shown coloured and arrows representing the airflow vectors. From this it can be seen that a downward draft develops within the channel fenced off by the flow guard (region 1), and that air then travels through the fins of the transformer and exits mostly on the inner side of the outlet. Recirculation is also present to the left of the plume of warm air rising from the transformer (region 2), suggesting that placing the outlet more centrally over the transformer in this ventilation configuration would aid in evacuating the hot air. This was not implemented here as it was assumed that this space would be occupied by the low voltage distribution cabinet. Figure 4.28 shows temperatures and velocities across the in- and outlet. These show velocities around 0.5 m/s and outlet air temperatures of approx. 52 °C.

Concluding this chapter, and looking back at the proposed research questions we can now show that it is possible to couple the *fin-slice* model to that of the vault, while

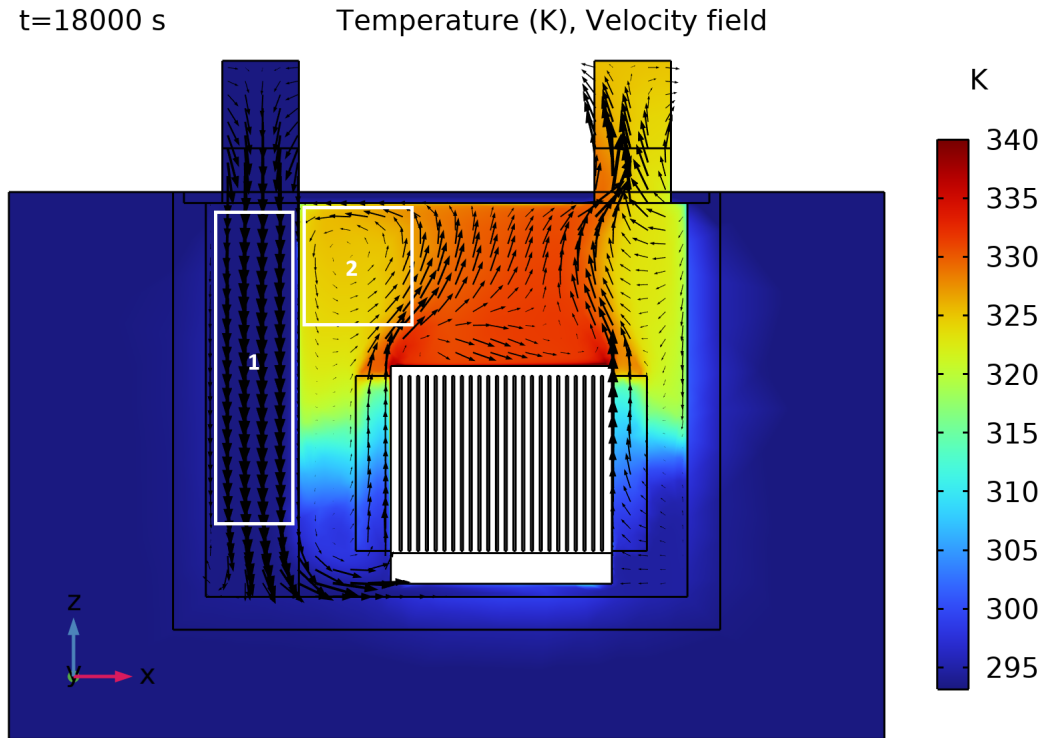
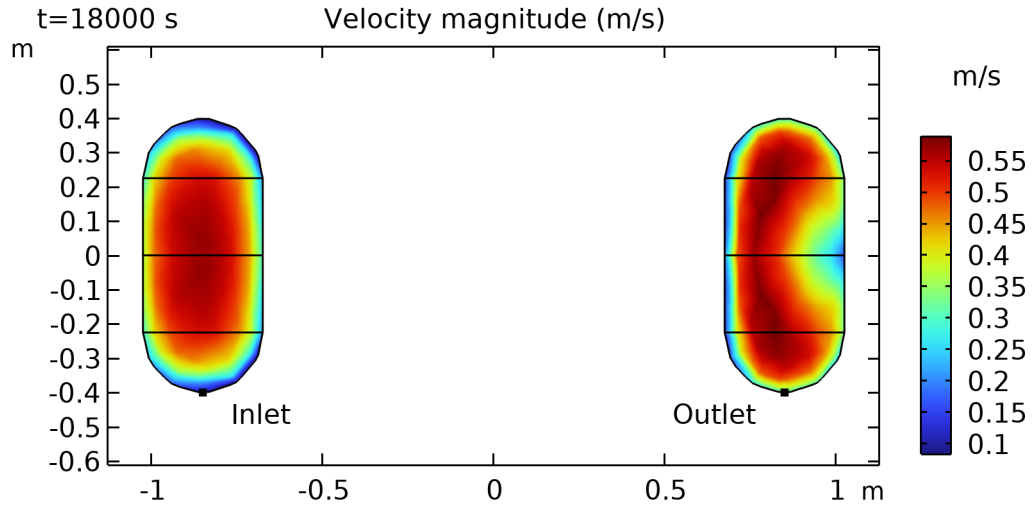
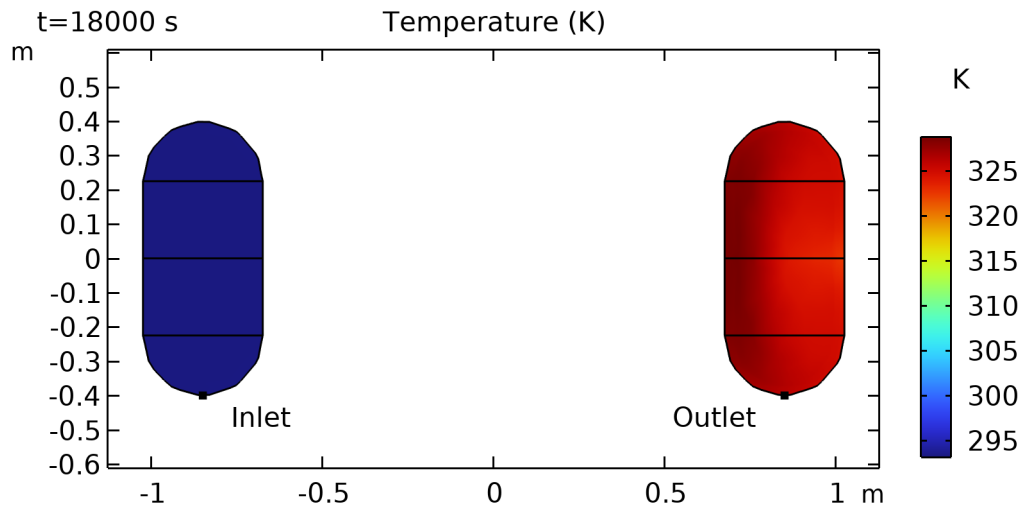


Figure 4.27.: Central slice of air temperature and flow field arrows. Arrow length proportional to flow velocity. Region 1 highlights the down draft, region 2 an area of recirculating air.

keeping calculation times within the time provided on a weekend, as long as meshes are kept at low resolutions. However, the accuracy of the model remains to be seen, and validation must be conducted via representative testing.



(a) In-/Outlet Velocities (m/s)



(b) In-/Outlet air temperatures (K)

Figure 4.28.: Cross sections of the in-/outlets of the vault model, taken 10 cm above ground level.

5. Testing of the Transformer

To validate the COMSOL model several representative tests were ran in the transformer laboratory of Alliander's subsidiary Qirion. The laboratory hall was sufficiently large to allow for temperature rise tests, while maintaining good ambient conditions. In these tests a representative above ground setup of the transformer in an underground vault was constructed, and load tested. The goal of these tests was to determine magnitudes of relevant parameters, such as top-oil temperature, for later comparison with the COMSOL models. To achieve this a test-plan had to be implemented and carried out. The chapter details conducted tests and achieved results.

5.1. The Transformer

The transformer used in the following tests was a 630 kVA three phase distribution transformer from Pauwels of type ENL100, constructed in 1992 according to NEN 2761-2765. The primary winding of this transformer is rated at 10250 V, 35.49 A on the central tap, and the secondary winding at 400 V, 909.3 A, with a short circuit voltage of 4 %. Both the primary and secondary winding are made of copper conductors. The full nameplate can be seen in Appendix G.1. As the transformer's losses and resistances were unknown at the start, measurements had to be done to determine these. The transformer had previously been operating in a distribution station, but was scheduled for decommissioning due to a fault in the station. It had also been opened for measuring the internal dimensions of the core and inductors. Failure inspections of the transformer, conducted before these tests by another team, revealed that the transformer was still fully functional and safe to use in these tests.

5.2. Preliminary Testing

Testing of the transformer was divided into multiple parts. Due to the transformer's age, type rating data was no longer fully available. All measurements were preformed with the tap-changer at position 5, resulting in a primary voltage of 9750 kV and a secondary voltage of 400 V. Preliminary testing was needed to determine load and no-load losses,

as well as the winding resistance at ambient temperature. Test procedures and relevant deviations from norms will be highlighted in the following sections.

5.2.1. Equipment

Resistance measurements were conducted with an IBEKO Power RMO60TD. Temperatures were measured with IEC 60584-1 Class 2 type T thermocouples, and logged to an SD-Card by Lutron BM-4208SD 12 channel temperature recorders. The thermocouples combined with the data-logger offer an accuracy of $\pm(1\text{ }^{\circ}\text{C} + 0.4\%)$ of the displayed value at an ambient temperature of $23 \pm 5\text{ }^{\circ}\text{C}$. Currents, Voltages and Powers were measured by a Fluke Norma 4000 power analyser. Three ring-type 50/1-0.2S current transformers from Eleq were used in conjunction with the Norma 4000 to measure currents. The power supply is a custom unit developed by Qirion, capable of delivering 0-750 V at a continuous output of 800 A, voltage regulation is handled by a variable autotransformer, see Fig. H.1. Airflow speeds were measured using a Testo 440 Hot Wire Kit utilizing a 0635 1032 hot wire anemometer from Testo, offering an accuracy of $\pm(0.03\text{ m/s} + 4\%)$ of the displayed value. Infra red (IR) thermography was available via a FLIR T620, though emissive values were not calibrated and so temperatures shown only allow for a qualitative analysis. Emissivity was set at an estimate for a painted surface of between 0.85-0.9.

5.2.2. DC-Resistance Measurement

Preliminary to other measurements winding resistances were measured, to ensure the oil did not warm from e.g. AC-loss testing. This was preformed with the transformer at ambient temperature. The resistances were measured using a single phase 4-wire setup, and an IBEKO Power RMO60TD, with a DC-current of 2 A for the primary winding's and 5 A on the secondary windings. Resistances were first measured on the secondary from 2u-2v, 2v-2w and 2w-2u. Followed by the primary side between terminals: 1U-1V, 1V-1W and 1W-1U. The measured values, and temperatures, were recorded for later evaluation and temperature correction. A schematic of the resistance measurement setup is presented Figure 5.1.

5.2.3. AC-Loss Measurement

Losses were not specified on the nameplate, and measurements to determine these had to be executed. To minimize thermal influence on the transformer no-load losses were measured first. Here the primary side was left open and the secondary side terminals (2u, 2v, 2w) were connected to the autotransformer, 2n was earthed. All three phases were measured simultaneously. Voltage meters were connected to the phase terminals,

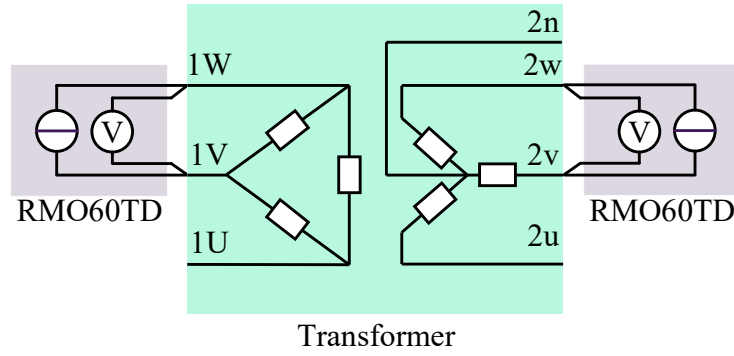


Figure 5.1.: Schematic representation of cold resistance measurement

and current was measured with the current transformers on the supply cable of each phase. With the Fluke Norma 4000 handling the measurements. The voltage was then increased until $U_{\text{nom}} = 400 \text{ V}$ was reached, and the measured value of real losses P was recorded.

To measure load loss the secondary winding's were short circuited and the autotransformer was connected to the primary of the transformer. Voltages and currents were measured separately for each phase, using the Fluke Norma 4000 and current transformers. Line voltage was slowly increased until the rated current, for tap setting 5, of 37.31 A was reached. The measured value of real losses P was then recorded. This measurement, combined with the resistances determined in 5.2.2 where then used to determine temperature corrected losses according to IEC 60076-1, and Annex E thereof [68]. Schematics of the measurement setup and connected meters can be found in Figure 5.2.

5.3. Temperature Rise Testing

5.3.1. Test Setups and Ventilation Geometries

To validate the thermal models created outlined in Chapter 4, representative experimental setups had to be built. Beside a free standing test, with the transformer in ambient, the two ventilation geometries, *box-* and *cabinet-setup* were implemented. The different testing configurations in the laboratory are shown in 5.3.

5.3.2. Testing Procedures

Temperature rise testing was based on IEC 60076-2:2011 with deviations in certain parts of the procedure [21]. Testing was preformed in three different setups, one free standing test in open air, and two tests with different ventilation geometries as previously defined in Chapter 3 and 4. To accelerate heating of the transformer it was chosen

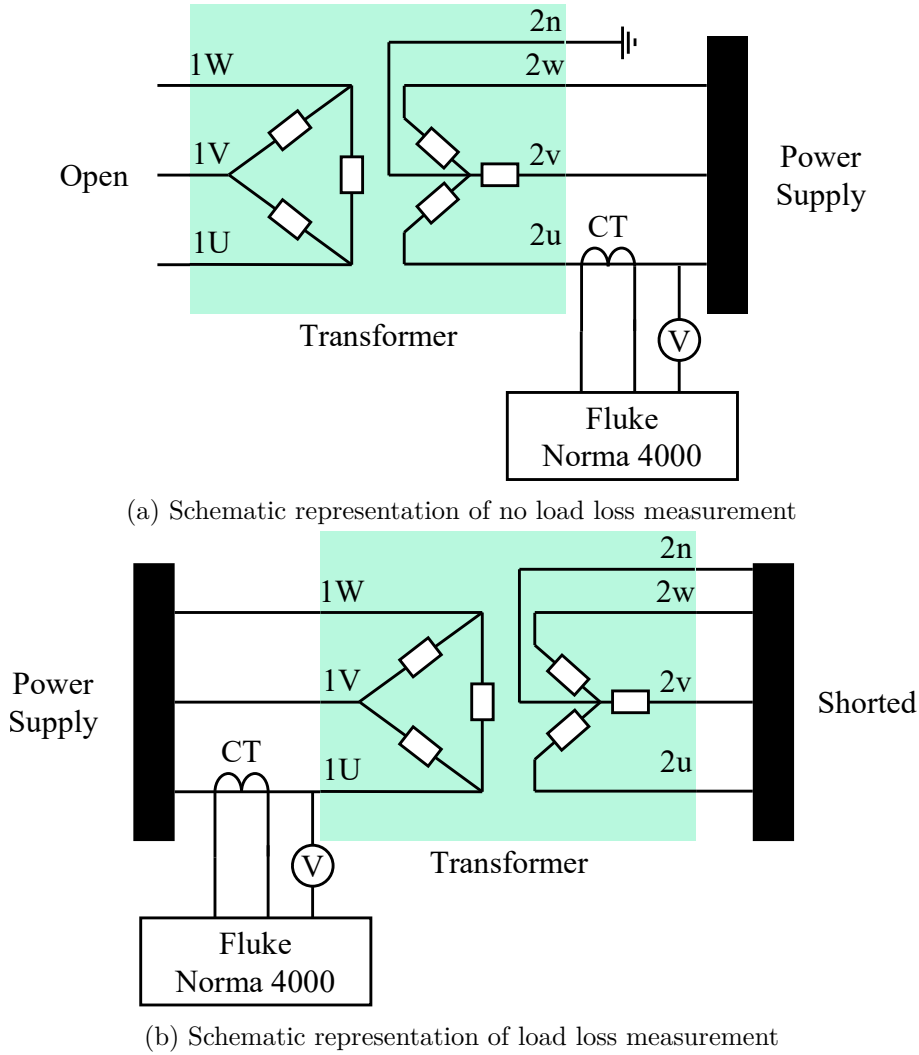
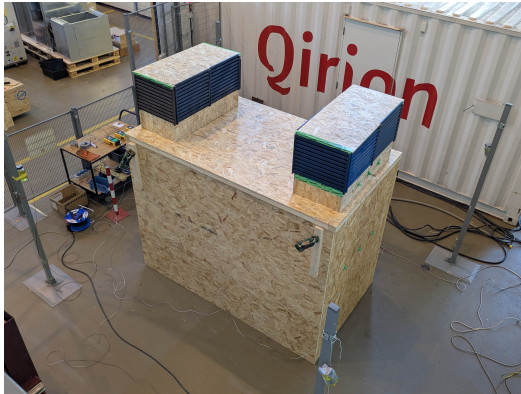


Figure 5.2.: Schematic drawings of loss measurements. One current transformer (CT) and Voltmeter was connected to each phase.

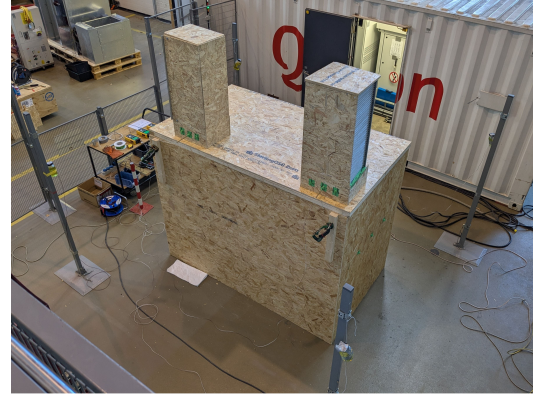
to overload the transformer during initial heating. The elevated heating current was 150 % of rated current, and was held until a temperature of 15 K below its predicted steady state temperature was reached, at which point the supplied current was reduced to the calculated value of 100 % of the corrected load loss. The second major deviation from standard testing was the stability termination criterion for top-oil temperature rise, where a rise of less than 1 K/h must be maintained for a period of 3 h. Testing times were limited to between 06:00 and 19:00 due to staff shift limits. As test duration would extend past 19:00 if this criterion were to be held, tests in this study were considered stable after a top-oil temperature rise of under 1 K/h had been maintained for 1 h. Temperature was measured using type T thermocouples placed on several different points on the transformer housing, as well as in- and outside the enclosure. Thermocouples measuring ambient air temperatures were placed inside glass vats filled with oil to eliminate fast fluctuations in air temperature. Thermocouples measuring



(a) Free Standing



(b) Vault 1



(c) Vault 2

Figure 5.3.: Different test setups in the Lab

air temperature on the inside of the enclosure were shielded from radiation with non conducting metallized tape and placed inside perspex tubing. Air currents were measured at the end of a temperature rise test by means of an handheld hot wire anemometer probe Testo 440 Hot Wire Kit, at three locations on the intake and outlet. Locations of sensors and their numbering can be seen in Figure 5.4. As well as relative to the fin-slice in Figure 5.5. Images of placed sensors can also be seen in Appendix H.3 Sensor Placement.

5.4. Results

Measurements of the three separate setups were conducted. The transformer was initially placed free standing and without a housing. Resistances and losses were then measured with the transformer at ambient. This was followed by the first temperature rise test with the transformer in open air. Concluding this the two vault designs, with Vault 1 and then Vault 2 were tested.

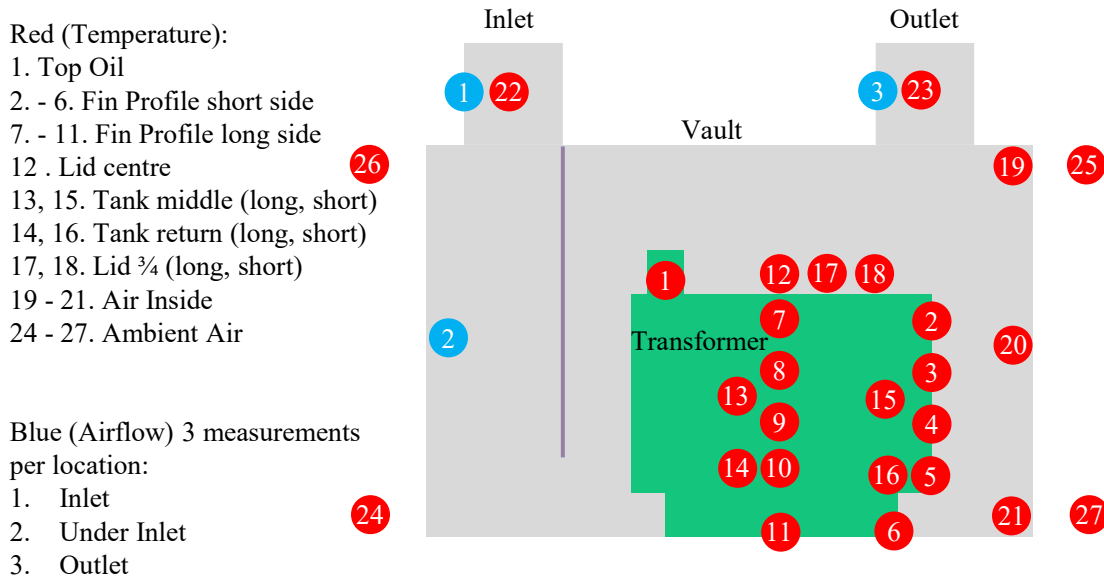


Figure 5.4.: Locations of thermocouples and flow measurements

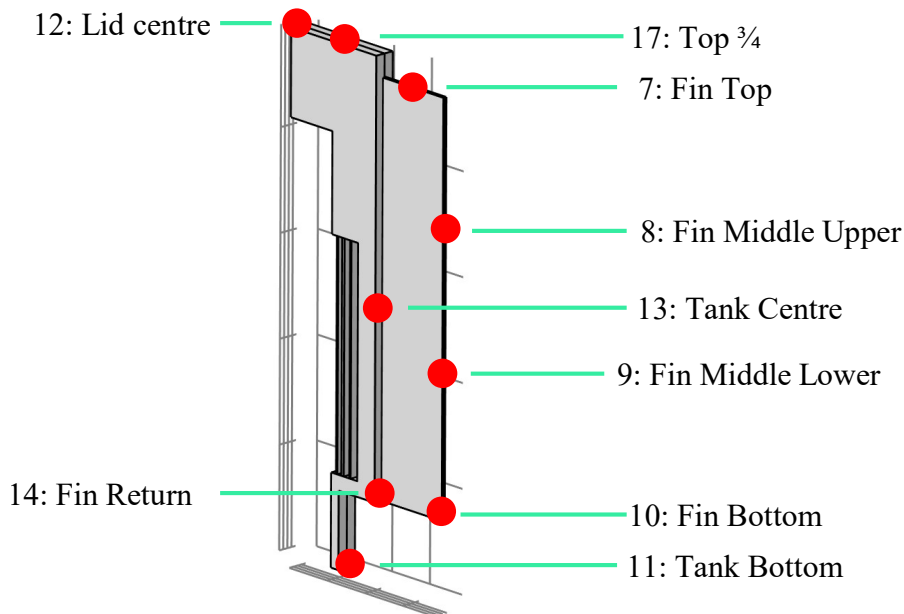


Figure 5.5.: Placements of thermal sensors on the long side relative to the fin slice

5.4.1. Transformer Characterization

Critical electrical parameters of the transformer were measured. Resistances and power losses were then corrected to 75 °C. Oil temperatures during these tests are shown in Table 5.1. The oil temperature was 22.4 °C

Results can be seen in Table 5.2. Due to the winding configuration (Dyn5) multiple resistances were measured when connecting two terminals and the measured values had to be corrected and then averaged accordingly for loss calculations.

Table 5.1.: Temperatures of transformer during characterization

Location	Temperature [$^{\circ}\text{C}$]
Top	22.9
Middle	22.6
Bottom	21.8
Average	22.4

Table 5.2.: Measured winding resistances

From - To	Resistance Measured	
	Primary [Ω]	Secondary [$\text{m}\Omega$]
U - V	1.289	1.496
V - W	1.262	1.493
W - U	1.257	1.526

No-load losses were measured before load loss. The results are presented in Table 5.3. Values shown are averaged across three phases.

Table 5.3.: Measured losses

	Measurement	
	No-Load Loss	Load Loss
$U_{\Delta \text{ r.m.s}}$ [V]	400.07	389.05
$I_{\text{r.m.s.}}$ [A]	3.734	37.390
Power [W]	926.6	5103.3
U_k [%]	-	3.99
Total Loss [W]	-	6029.9
Tot. Loss @ 75 $^{\circ}\text{C}$ [W]	-	6849.8

No-load and load losses were 926.6 W and 5103.3 W respectively, for a total loss of 6029.9 W at 22.4 $^{\circ}\text{C}$. Using the measured resistances and losses, a corrected loss of 6849.8 W was obtained at 75 $^{\circ}\text{C}$. This is the value which will be held as nominal loss during temperature rise testing.

5.4.2. Temperature Rise Testing

Temperature rise testing was completed, with the top-oil temperature stabilizing at a rate of < 1 K/h at the end of testing. Results of select temperature and flow probes can be seen in Table 5.4, these were taken at the time of reaching thermal stability. Sensors detailing the fin profile in this table represent sensors placed on the long side. A full

table with all sensors at steady state can be found in Appendix H.1. IR-images are presented in Appendix H.4.

Table 5.4.: Select measured temperatures, velocities, and differences (Δ_{Free}) of Vault 1, 2 to the free standing setup

	Test Run				
	Free Standing	Vault 1	Δ_{Free}	Vault 2	Δ_{Free}
Avg. Ambient [$^{\circ}\text{C}$]	24.0	24.0	0.0	23.5	-0.5
T_{TopOil} [$^{\circ}\text{C}$]	77.3	89.8	12.5	93.9	16.6
$\theta_{\text{TopOilRise}}$ [K]	53.3	65.8	12.5	70.5	17.2
T_{FinTop} [$^{\circ}\text{C}$]	75.8	88.5	12.7	92.6	16.8
T_{FinUpper} [$^{\circ}\text{C}$]	63.0	77.8	14.8	83.8	20.8
T_{FinLower} [$^{\circ}\text{C}$]	58.5	69.8	11.3	73.5	15.0
$T_{\text{FinBot.}}$ [$^{\circ}\text{C}$]	53.8	63.9	10.1	68.1	14.3
$T_{\text{TankBot.}}$ [$^{\circ}\text{C}$]	41.4	48.5	7.1	49.4	8.0
$T_{\text{FinReturn}}$ [$^{\circ}\text{C}$]	51.4	59.2	7.8	60.0	8.6
$T_{\text{LidTop3/4}}$ [$^{\circ}\text{C}$]	63.9	85.0	21.1	89.0	25.1
$T_{\text{LidTopCenter}}$ [$^{\circ}\text{C}$]	68.2	84.7	16.5	88.8	20.6
$T_{\text{AirVaultTop}}$ [$^{\circ}\text{C}$]	-	60.9	-	65.7	-
$T_{\text{AirVaultMid.}}$ [$^{\circ}\text{C}$]	-	46.3	-	57.5	-
$T_{\text{AirVaultBot.}}$ [$^{\circ}\text{C}$]	-	32.1	-	33.0	-
T_{AirIn} [$^{\circ}\text{C}$]	-	25.3	-	24.1	-
T_{AirOut} [$^{\circ}\text{C}$]	-	63.5	-	66.5	-
v_{in} [m/s]	-	0.30	-	0.91	-
v_{wall} [m/s]	-	0.30	-	0.10	-
v_{out} [m/s]	-	0.28	-	0.77	-

To note is that during the temperature rise test of Vault 3 temperature sensor Nr. 2 "L1 - 2 Fin Top" came lose and the reading is therefore no longer representative, see Figure 5.6.



Figure 5.6.: Detached thermocouple Nr. 2 "Fin Top" on the short side of the transformer

5.5. Discussion

Free standing top-oil temperatures reached 77.3 °C, or 53.3 K above ambient. Testing inside the vault under lid 1 and 2 revealed temperatures, and rises of 89.8 °C, 65.8 K and 93.9 °C, 70.5 K respectively. For lid 1 the top-oil temperature rise was 12.5 K above the free standing transformer, and for lid 2 17.2 K. Both of these values lie within the specified temperature class of 20 K. As temperatures were considered stable after one hour, a further rise of 1-2 K top-oil temperature must be taken into account if the 3 h criterion from the IEC norm were to be upheld. Future testing with modern distribution transformers would, however, reveal more advantageous thermal performance, as these are specified with a lower maximum total loss of 5140 W, approximately 900 W lower than the tested transformer. It must however also be said that the temperature rise in both vaults exceeds the maximum temperature rise limit of 60 K, listed in IEC 60076-2, which could possibly mandate a de-rating of the transformer [21]. Higher (short term) temperatures might be permissible under load ratings according to IEC 60076-7 [22].

Flow speed measurements show an, unexpected, lower flow velocity on the outlets (v_{out}) compared to the inlets (v_{in}). This is probably an erroneous measurement stemming from the use of a hot wire anemometer. Flow velocities were measured and averaged over one minute. This might however, not have been enough time for the temperature of the hot wire anemometer to fully stabilize, ergo, the outlet shows a lower velocity than what would be expected. Lab safety demanded a shut-off of the electric supply to prevent electrocution before manually placing the anemometer in the measurement slots. Measurements had to therefore be preformed quickly after shut-off, to capture the flow field as accurately as possible. In future testing this could be improved by permanently placing an anemometer without the need for manual operation.

During the end of testing Vault 2, infrared images were taken. Of special note here is the outlet of Vault 2, shown in Figure 5.7b. A temperature gradient between the lower edge of the right facing ventilation grille and the top edge can be observed. This effect can also be seen to a lesser degree in the left facing grille. It would appear that cold air is being drawn into, or over the lower section of the grilles, causing a reduction in their effective surface area. A possible explanation here is that the rising warm air creates a suction while passing along the grilles vertically, drawing cold, ambient air in, and upwards to the exhausting section. Another possible, albeit less likely, phenomena could be cold air entering the grilles, and sinking down into the vault. The second reason appears less likely, as the top region of the ambient air is hot (65.7 °C), and would push against any airflow down into the transformer's chamber through this opening.

The collected temperature profile measurements of the transformer's tank and fins, air temperatures on the in- and outlet, air temperatures inside the vault and flow velocities will be used to validate the CFD model in the following chapter.

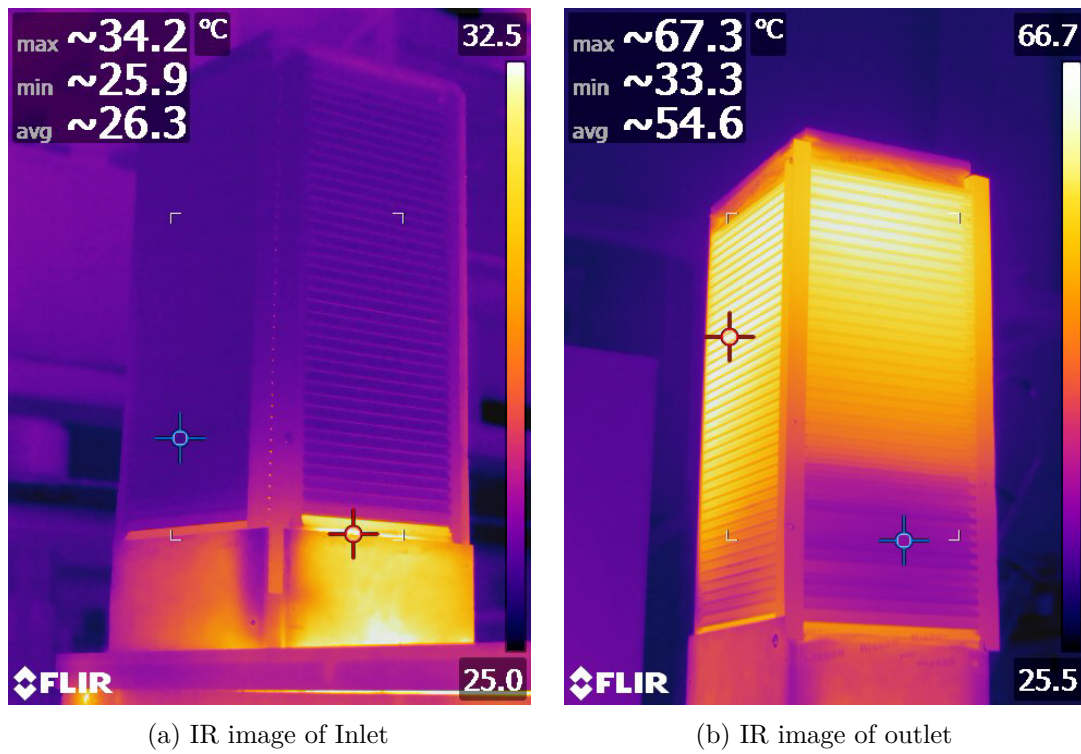


Figure 5.7.: IR-images of inlet and outlet of Vault 2, $\varepsilon = 0.9$.

6. Model Validation and Design Discussion

After testing was performed the models could be updated with geometries and power loss results obtained and used in Chapter 5. This chapter outlines the changes made to the COMSOL-models, as well as the newly obtained simulation results thereof. Discrepancies and model performance is briefly discussed for the separate models. Following the model evaluation three design variants of the *cabinet-setup* are evaluated, with the aim of improving thermal performance, or minimizing the required volume. Concluding this chapter these adjusted models and possible improvements are then discussed.

6.1. Adjusted Losses and Geometries

Corrected power losses from testing (Tab. 5.3) were used in conjunction with equations 4.8 - 4.10 to update the losses in the COMSOL model, shown in Table 6.1. While the heat flux of the LV windings only increased marginally, larger changes can be seen in the heat fluxes of the core and HV-windings. Increases in core losses can be attributed to an older transformer specification, in which the cores had not yet been magnetically optimized. Copper losses in the HV windings of this older transformer were also much higher than permissible in those specified for newer transformers, and the split of LV:HV losses is also not 50:50 as assumed in the preliminary calculations.

Table 6.1.: Losses and heat fluxes adjusted for measurements

Component	$P_{N,meas}$ [W]	q [W/m ²]	$q_{init.}$ [W/m ²]
Core	927	390.64	227.66
LV	2490	538.92	497.81
HV	3433	624.01	418.03

Furthermore in- and outlet geometries of the COMSOL model were adjusted to match those from testing. The *box-setup* in-/outlet was a cuboid with a length x width x height of 1001 mm x 430 mm x 400 mm, while that of the *cabinet-setup* was 350 mm x 380 mm x 805 mm.

6.2. Free Standing Validation

To simulate the free standing temperature test the *fin-slice* model was simulated on its own as a time dependent simulation, at an ambient temperature of 23 °C. To save calculation time the model was initialized with an extra coarse mesh, and then continued with the *coarser* mesh. Steady state was assumed to be reached when top-oil temperature change was less than 1 K/h. This occurred after a time of 7500 s in the *coarser* setting.

A comparison of select temperature values along the outside of the fin can be seen in Figure 6.1 and Table 6.2. It can be observed that calculated temperatures match well with measured values, with differences under 5 K. Calculated values for the top-oil temperature are 2.9 K higher than those measured, providing an overestimate for this setup. This overestimation then slowly transitions into an underestimation for the lower regions of the transformer.

This observation can be partially explained by the present application of the Boussinesq approximation (see Appendix C), and it is assumed that the error may become more consistent, if a flow regime without this approximation were applied. The slightly larger variation of the *fin return* point could possibly be due a mismatch of the sensor location in the lab, compared to the probe location in the simulation, as the fins surface temperature shows quite high variation in the return region (Fig. 1.1a).

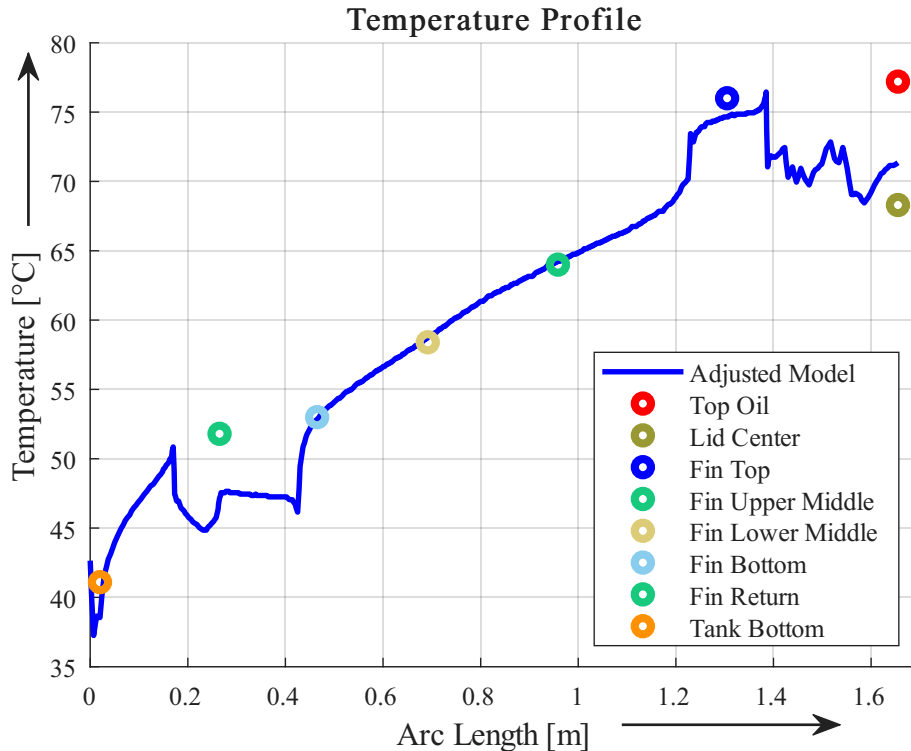


Figure 6.1.: Free standing transformer: Temperature profile on outside of the fin. Dots represent measured values in the lab, line represents the simulation.

Table 6.2.: Select temperature sensor values compared to simulation: Free Standing

Sensor	Lab Test [°C]	Simulation [°C]	$\Delta\text{Sim.} - \text{Lab}$ [K]
T_{TopOil}	77.3	80.2	2.9
$\theta_{\text{TopOilRise}}$	53.3	56.2	2.9
$T_{\text{LidTopCenter}}$	68.2	71.4	3.1
T_{FinTop}	75.8	74.7	-1.1
T_{FinUpper}	63.0	64.3	1.3
T_{FinLower}	58.5	58.8	0.3
$T_{\text{FinBot.}}$	53.8	52.9	-0.9
$T_{\text{FinReturn}}$	51.4	47.6	-3.8
$T_{\text{TankBot.}}$	41.4	38.6	-2.8

6.3. Box-Setup Validation

The simulation for the *box-setup* was initialized as described in Section 4.7, but as a longer simulation slot was available the low Reynolds step was conducted with a *coarse* mesh for both the *fin-slice* and vault model¹. Ambient temperatures were set to 23 °C, and the K-factor of the in-/outlet gratings to 80. Steady state was reached in the low Reynolds step after a simulated time of 6600s.

Table 6.3 and Figure 6.2 show a comparison of select sensor values with those of the simulation. Temperatures in the *fin-slice* model still agree with those measured in the lab, although the average temperature error has increased. The outside temperature profile shows a general underestimation of fin temperatures in the model by 1-6 K, while top-oil temperature still agrees well with that measured in the lab. The overestimation of top-oil temperature is however reduced compared to the free standing model (0.5 K v.s. 2.9 K). Furthermore, large discrepancies of above 15 K can be seen in air temperatures of the vault.

These discrepancies could suggest that the thermal load of the model might be too low, or that heat transfer on the boundaries of the transformer was inadequately modelled. This could possibly be explained by the chosen wall treatment in the vault model (automatic), and might be rectified by enforcing an approach without wall functions, and resolving the flow regime up to the walls. Using Table 6.3 to calculate the heat flow rate [W] in the outlet using:

$$h = Q C_P \rho \Delta T \quad (6.1)$$

where Q [m³/s] is the volumetric flow rate across the outlet, c_P [J/(kgK)] the isobaric heat capacity ρ [kg/m³] the density and ΔT [K] the difference in in-/outlet temperature, results in an $h_{\text{measured}} = 4860$ W and $h_{\text{simulated}} = 3430$ W, Initial testing of two designs,

¹Computation time: 148h

involving different ventilation geometries, showed top-oil rises of 13-17 K compared to the free standing transformer, a difference of 1430 W.

Flow velocities on the in and outlet are in acceptable agreement. At the indicated velocities the measured error would be 0,06 m/s. Flow speed measurements are also heavily dependent on location, as shown in speed outlines in Figure I.4. Should the probe have been located slightly of target in the measurement, different results may have been obtained.

Finally, compared to the initial simulation of the *box-setup* in Chapter 4, we observe a lower final top-oil temperature of 90.4 °C compared to 95.6 °C.

Table 6.3.: Select sensor values compared to simulation: Box-setup

Sensor	Lab Test	Simulation	Δ Sim. - Lab
T_{TopOil} [°C]	89.8	90.4	0.6
$\theta_{\text{TopOilRise}}$ [K]	65.8	67.4	1.6
$T_{\text{LidTopCenter}}$ [°C]	84.7	80.8	-4.0
T_{FinTop} [°C]	88.5	85.0	-3.6
T_{FinUpper} [°C]	77.8	74.1	-3.8
T_{FinLower} [°C]	69.8	68.6	-1.3
$T_{\text{FinBot.}}$ [°C]	63.9	63.0	-0.9
$T_{\text{FinReturn}}$ [°C]	59.2	53.6	-5.7
$T_{\text{TankBot.}}$ [°C]	48.5	44.9	-3.7
$T_{\text{AirVaultTop}}$ [°C]	60.9	44.1	-16.8
$T_{\text{AirVaultMid.}}$ [°C]	46.3	34.3	-12.0
$T_{\text{AirVaultBot.}}$ [°C]	32.1	24.3	-7.8
T_{AirIn} [°C]	25.3	23.0	-2.3
T_{AirOut} [°C]	63.5	46.1	-17.4
v_{in} [m/s]	0.30	0.42	0.12
v_{wall} [m/s]	0.30	0.34	0.05
v_{out} [m/s]	0.28	0.31	0.03

6.4. Cabinet-Setup Validation

The *cabinet-setup* was also simulated as described in Section 4.7 and akin to the Box-setup, however extra-coarse meshes were used due to calculation time constraints. Ambient temperatures were set at 22.6 °C, corresponding to the average ambient temperatures during testing. K-factors of the in-/outlets were set to 25, approximately corresponding to the grating geometries used in testing [67]. With these settings a steady state was reached in the low-Reynolds step after a simulated time of 13,800 s.

Select results of this calculation can be seen in Table 6.4 and Figures 6.3, 6.4. Overall trends and patterns from temperatures between the test and simulation are similar to

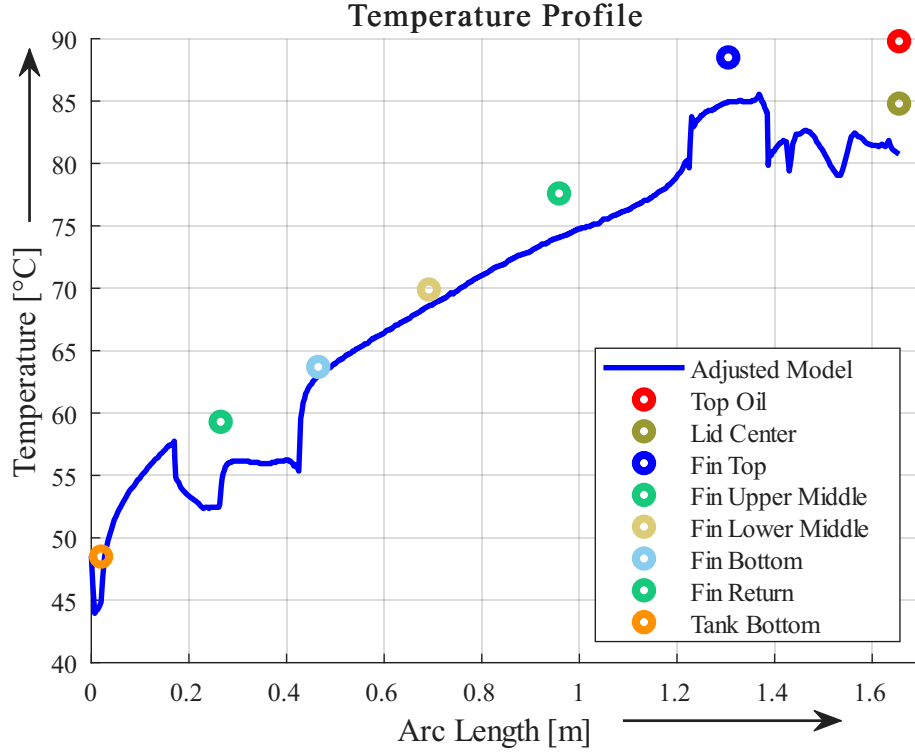


Figure 6.2.: Temperature profile on outside of the fin. Dots represent measured values in the lab. Line represents the simulation.

those in the *box-setup*. With a slight overestimation of top-oil temperature (rise), albeit smaller than in the free-standing simulation. Furthermore, the temperature profile again underestimates the temperature rise at the top of the transformer. Air temperatures are also underestimated to a large degree, nearly 17 K in the worst case. Applying the results in Table 6.4 to Equation 6.1 yields: $h_{\text{measured}} = 4550 \text{ W}$ and $h_{\text{simulated}} = 3850 \text{ W}$; a difference of 700 W.

Flow velocities are in general agreement with those measured. The inlet velocity (v_{in}) being slightly lower in the simulation agrees with the lower simulated air temperatures. Outlet velocities (v_{out}) are slightly higher than measured, though this could once again be due to the possibly erroneous measurement of said velocity discussed in Section 5.5.

The larger underestimation of the fins temperature profile, compared to the test data, can probably be explained by the convective boundary condition applied to the *fin-slice* model, in which ambient air temperature is passed as a constant (averaged) value. When however observing the air temperature inside the vault, as shown in Figure 6.4, it can be seen that the ambient air temperature at the top of the transformer is 10-20 K warmer than that at the bottom. This change could be reflected in a future version of the *fin-slice* model, by implementing a temperature gradient onto the relevant boundary conditions. Underestimated air temperatures could, akin to the *box-setup*, be a sign of inadequate thermal load, or choice of the wall treatment in the flow regime. Another possible cause

in these simulations is the use of an coarse mesh, under which the application of wall functions is more common, leading to a worse estimation of heat transfer between the transformer and air. Albeit, the conducted mesh study would not indicate so. A final, possible cause for this, is the recirculation seen in areas 2 and 3 of Figure 6.4. Should these recirculation patterns differ strongly in the test setup and model, the difference in mixing of cold and warm air could also cause the difference in observed and simulated air temperatures.

First possible design improvements can also be garnered from the flow patterns obtained in the simulation. Figure 6.4 shows three regions of very low flow velocity/recirculation (also visible in I.7). Region 1 is in the down draft section, under the intake and the flow-guard, while region 2 and 3 occur in the corners above the transformer, where the rising hot air cannot immediately escape. It is assumed that interrupting these will have a net benefit on cooling, either by better guiding the incoming cold air into the transformer, or better evacuating the rising warm air, and directing it towards the ventilation. The effects of this, and other potential improvements, on top-oil temperature can now be tested on the validated COMSOL model.

Table 6.4.: Select sensor values compared to simulation: Cabinet-setup

Sensor	Lab Test [°C]	Simulation [°C]	$\Delta\text{Sim.} - \text{Lab}$ [K]
T_{TopOil} [°C]	93.9	94.5	0.5
$\theta_{\text{TopOilRise}}$ [K]	70.5	71.9	1.4
$T_{\text{LidTopCenter}}$ [°C]	88.8	84.0	-4.8
T_{FinTop} [°C]	92.6	87.9	-4.8
T_{FinUpper} [°C]	83.8	77.7	-6.1
T_{FinLower} [°C]	73.5	72.3	-1.3
$T_{\text{FinBot.}}$ [°C]	68.1	66.9	-1.3
$T_{\text{FinReturn}}$ [°C]	60.0	61.6	1.6
$T_{\text{TankBot.}}$ [°C]	49.4	52.4	3.0
$T_{\text{AirVaultTop}}$ [°C]	65.7	52.6	-13.1
$T_{\text{AirVaultMid.}}$ [°C]	57.5	41.2	-16.3
$T_{\text{AirVaultBot.}}$ [°C]	33.0	26.5	-6.6
T_{AirIn} [°C]	24.1	22.6	-1.5
T_{AirOut} [°C]	66.5	52.8	-13.7
v_{in} [m/s]	0.91	0.83	-0.09
v_{wall} [m/s]	0.10	0.17	0.08
v_{out} [m/s]	0.77	0.88	0.11

6.5. Design Variations

Preliminary, to a potential sensitivity analysis, some model variations were conducted to analyse the impact of geometry adjustments of the existing features in e.g. width

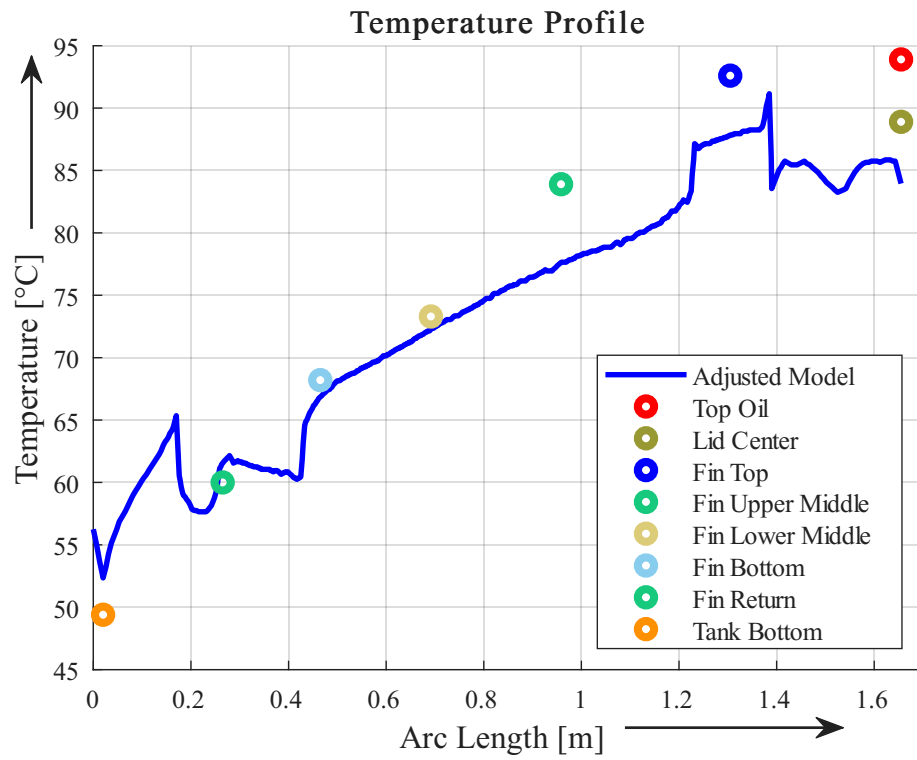


Figure 6.3.: Temperature profile on outside of the fin. Dots represent measured values in the lab. Line represents the simulation.

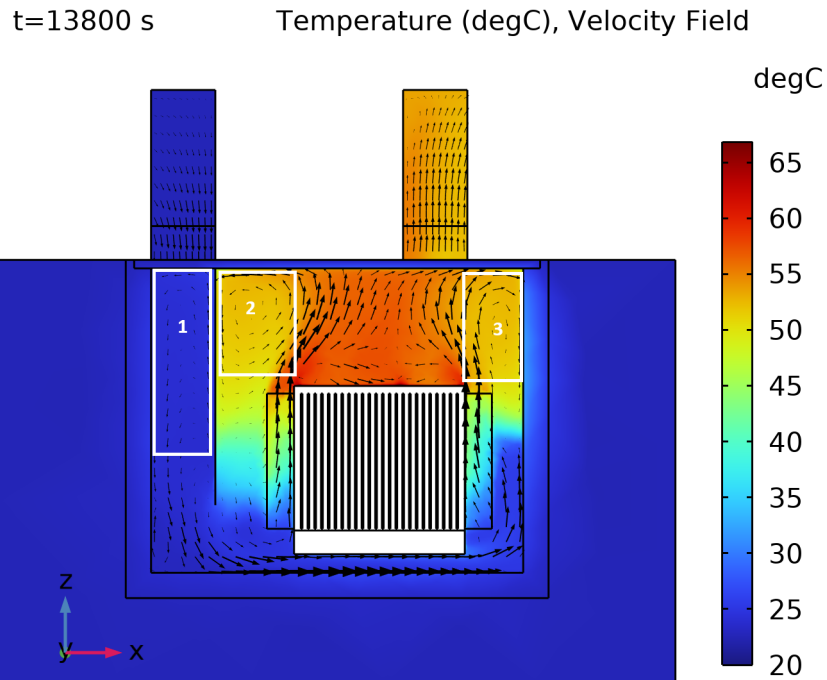


Figure 6.4.: Cross sectional temperature and flow field in the vault. Arrows only show velocity in x and z directions, length proportional to velocity magnitude.

and height, as well as implementing new features. Three designs were studied:

- **Minimal Vault Dimensions:** the interior width, height and length of the underground vault was dimensioned such that the width would fit a standard 630 kVA distribution transformer plus 50 mm of buffer to the walls. The length was limited by the dimensions of the distribution cabinet and the width of the ventilation towers, while the depth was designed with 20 kV ceramic-insulators, plus a safe margin. This resulted in a final (l x w x h) of the under ground vault's inner walls of (1.87 x 0.9 x 1.6) m. Taking into account 0.15 mm thick walls an area of 2.6 m² is achieved.
- **Flow Guard:** The volume behind the flow guard in which the incoming air drafts down showed significant recirculation in the simulations of the *cabinet-setup*. To prevent these the flow guard was altered such that it now fills the majority of the volume. Furthermore a block was added which represents the incoming cables, a larger restricted flow area due to the LV-distribution cabinet. These were modelled as solid concrete blocks, and can be seen in Figure I.8.
- **Larger Ventilation:** IR-Thermography during testing showed that the lower portion of the outlet gratings probably do not contribute to evacuating warm air, to improve the in and outlet it would therefore be advisable to make them wider or deeper, instead of higher. Furthermore an extra rise of the underside of the in-/outlet was considered to ensure better working height on the LV-cabinet. This resulted in a ground distance of the underside of the ventilation of 0.5 m, as well as a (w x d x h) of a single ventilation tower of (0.55 x 0.35 x 0.8) m. Resulting in an in-/outlet area of 0.72 m², a 29 % increase compared to the initial design.

The impact of these changes on the predicted top-oil temperature, compared to the initial model, was simulated and can be seen in Table 6.5, and cross sections of the internal temperatures of each variation are shown in Figure 6.5.

Table 6.5.: Top Oil Rise in different Variations

	Initial Model	Min. Dim.	Flow Guard	Larger Vent.
$\theta_{\text{TopOilRise}}$ [K]	71.9	70.3	68.9	66.3
Δ to initial [K]	-	-1.6	-3	-5.6

It can be seen that all three variations have a positive effect on the predicted top-oil temperatures, with reductions of up to 5.6 K when using wider intakes. Minimizing the dimensions of the enclosure has the positive effect of eliminating the recirculation in region 2 and 3 mentioned earlier (see Fig.6.4). Although air temperatures at the top of the vault, and also at the outlet, increase. While for both the flow guard variation, and

the wider ventilations the air temperatures inside decrease, compared to the original design.

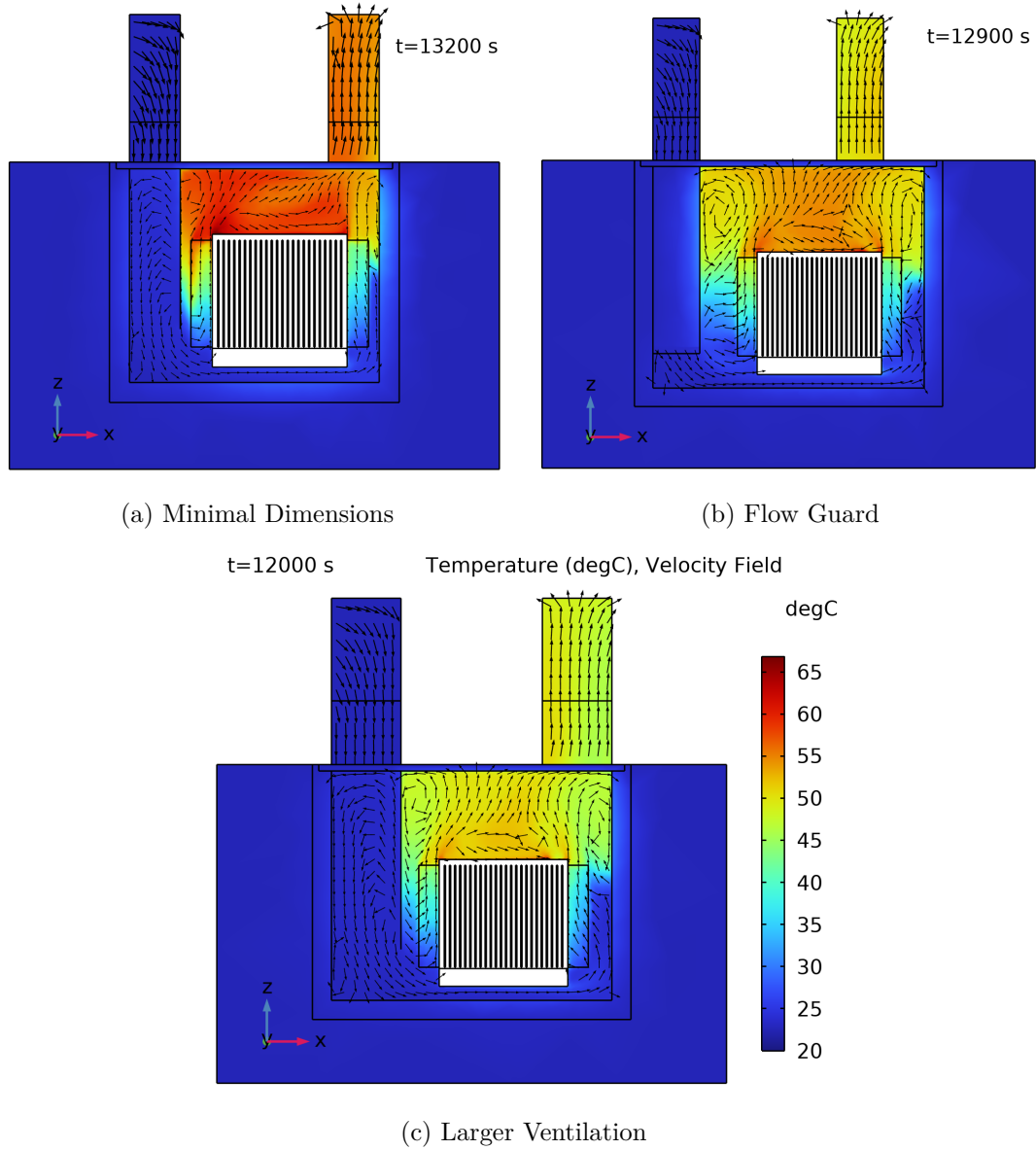


Figure 6.5.: Variations of the *cabinet-setup*. Slice through centre of vault, and centres of in-/outlets. Arrows indicate flow directions in x, z axis, lengths normalized. Time indicates time taken to reach steady state in the low-Reynolds step. Temperature scale equal for all plots.

6.6. Discussion, Improvements and Future Work

Validating all three models, free standing, *box-* and *cabinet-setup* showed promising and robust results for top-oil temperature (rise) prediction, where deviations were under 3 K compared to lab testing. Smaller deviations in temperature along the outside of the fin

profile arose when combining the vault and *fin-slice* model in a single calculation, however these can probably be attributed to the nature of the defined boundary conditions. All tested and simulated transformer vaults showed a temperature rise of under 20 K, compared to the free standing setup, hereby reaching an enclosure class of 20 K. Larger discrepancies in the air temperatures however need addressing, and in future calculations it is advised to refine the mesh along the transformer's boundaries, and employ simulation methods that better capture heat transfer in this region.

Modifying the ventilation or vault geometries of the *cabinet-setup* showed further promising results, with all three variations reducing top-oil temperature rises, compared to the original design. Assuming the effects of the flow guards and wider intakes are cumulative, a total reduction of up to 8-9 K is achieved, resulting in a top-oil temperature rise of only 63-64 K. Should this be the case the enclosure would reach a temperature class of 10 K (temperature rise of free simulated transformer was 56.2 K). Although this claim would need to be validated with additional lab testing. Assuming a cumulative effect of the flow guard and a setup with minimal dimensions, a temperature rise of approx. 69 K is reached, or 13 K higher than if the transformer were free standing, placing this enclosure at a temperature class of 20 K. With potentially high temperature rises, it remains key to enable an as smooth airflow as possible, by ensuring minimal restrictions for the natural convection. Large ventilation openings probably have the largest effect here, but optimizing airflow, via recirculation prevention, or low resistance ventilation gratings remains key in the cooling performance of underground substations.

The design evaluating the *minimal vault dimensions* demonstrates a minimum required area of 2.6 m². Currently the smallest compact substation deployed by Liander has a footprint of approximately 7.0 m² ². This new minimal design would therefore ensure a significant reduction in the required area of 62.9 %, less than half that of the traditional substation. Not included here are the clearance zones needed for the doors, including these would ensure even greater reductions in the required area. Furthermore, the above-ground volume is reduced by 91.6 %, to less than one-tenth of the original volume, the compact substation requires 9.2 m³, whereas the underground substation requires only 0.77 m³ in the current design.

Many questions still remain to be answered before a substation of this type can be deployed. A few of which are critical for future long term operation and investigation. A full, buried, test setup will therefore also need to be constructed, on which some of these open questions can be tested. For instance, the question of moisture in the station must be answered: can the underground vault reattain safe moisture levels once buried, under the given ventilation setup? Or can incoming warm, humid air in summer, lead to accumulation of humidity with colder temperatures underground? Furthermore, work safety must be provided for service staff working on the construction/maintenance

²A variant of the Alfen Diabolo 20H.

of these substations. Here the questions about working position when accessing the transformer (station cannot be entered) as well as safe grounding and cable routing must be analysed in depth. Finally, grid integrations of these substations, and their possible branched design on the typical ring-MV grid also needs to be investigated. Questions such as maintaining N-1 and safe grid operation and switching remain.

Aside from these design, operation and safety requirements, the COMSOL model itself can also still be improved. Some boundary conditions of the *fin-slice* in the linked model could be adjusted to better reflect air temperature gradients within the station. While the underground part of the station could have a lower ambient temperature, if outside, underground testing becomes available. Additionally, a quick inspection of the flow profiles between the fins of the transformer showed a stabilization in the mid-upper regions of the fins (see Fig. I.10). At this point the natural convection no longer mirrors that of an external convection along a vertical wall, but more closely matches that of an internal convection in a *narrow chimney*, at which the calculation of h changes slightly. Testing the effect of this implementation is left to future work. Calculation time could be saved by initializing the *fin-slice* model before calculation of the whole model. This would need to be done once, and the initialized *fin-slice* could then be re-used for all future simulations. Although to achieve this larger changes in the solver structure are needed, as initializing the fin in the linked model would result in missing ambient temperatures. COMSOL offers functions to work around this, but implementation and testing of these are not trivial. During simulations it was also noted that the calculation time can be extremely dependent on both mesh fidelity, and geometry layout of the vault models. Further work on mesh refinement could help in reducing computational times further. Once this is achieved more in depth optimization via sensitivity studies, and parameter optimization of the vault's geometry can be conducted within COMSOL, with the goal of further reducing and minimizing top-oil temperature rise.

7. Conclusion

Increasing demand for electricity in the Netherlands and within Lianders's distribution grid is driving the need for infrastructure expansion. City centres of older, larger towns present a unique challenge, as space comes at a premium, and finding locations for new distribution substations has become increasingly difficult. Resistance to the deployment of new substations stems not only from residents but also from city councils and land management authorities. To enable further progress in grid expansion new types of substations must be employed. This study analysed potential designs for an underground substation, which would allow for easier integration of substations in these dense city centres. As previous studies within Liander had shown transformer cooling to be a challenge, it was chosen to first analyse the potential solutions of this before progressing with future studies and engineering of the underground substations design. Based on standards set for substations an enclosure class of 20 K was desired, under the employment of a 630 kVA transformer.

To analyse the predicted cooling performance and possible variations a 3D-CFD model was implemented in COMSOL-Multiphysics, partially based on previous work by Gastelurrutia et al. in [55]. The model implemented in this work consisted of two linked 3D sub-models, which can exchange critical parameters with each other. The first model represents the oil inside the transformer, while the second models the heat and mass transfer phenomena within the underground substation. With these models it was possible calculate and predict top-oil temperature (rise), as well as airflow and temperatures inside the underground substations vault, while keeping calculation times under 64 hours in most cases.

Validation of the developed models was achieved through representative tests conducted in the high-voltage laboratory. Initial testing of two designs, involving different ventilation geometries, showed top-oil rises of 13-17 K compared to the free standing transformer. The results obtained allowed for adjustments in the model, and provided crucial information about temperatures as well as flow speeds inside the substation. Calculated temperatures of the *fin-slice* model showed excellent agreements with test data from the lab, with differences in top-oil temperatures of under 3 Kelvin. While the proposed designs all achieved a temperature class of under 20 K, in simulations and testing, in accordance with standards set by Liander. Larger discrepancies, of up to

16 K, however remained between the air temperatures inside the simulated underground vault, and the test setup in the lab.

Utilizing the validated models, three variations of a potential substation design were evaluated. These consisted of a vault with minimal dimensions, a different approach to recirculation management, as well as a setup with larger ventilation surfaces. The primary aim was to analyse the impact of geometric changes of the underground vault and ventilation on the transformer's top-oil temperature rise. All three simulated setups resulted in a reduction of top-oil temperature rise, with a reduction of top-oil temperatures of up to 5 K in a single measure. These results suggest that a temperature class of 10 K might be reachable with further design optimization.

If a temperature class of 20 K be deemed acceptable, then the minimal design could serve as the basis for further developments. Assuming that it is possible to keep the proposed footprint, the new underground substation would allow for significant savings in land use (a reduction of at least 62.9 % compared to existing compact substations) and, most notably, a reduction of 92.6 % in above-ground volume.

In conclusion, this research demonstrates that the thermal challenges of urban underground substations can be effectively managed within the specified constraints. While this study establishes a robust foundation for predicting top-oil temperature rise, future work on safety, moisture management, and grid integration is required to demonstrate the full-scale implementation of underground substations within Liander's distribution grid. Ultimately, the fast transition to a resilient, high-capacity urban grid must rely on such infrastructure solutions to maximize public acceptance and minimize deployment times, so that the growing electricity demand can be met in city centres.

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A. Design Finding

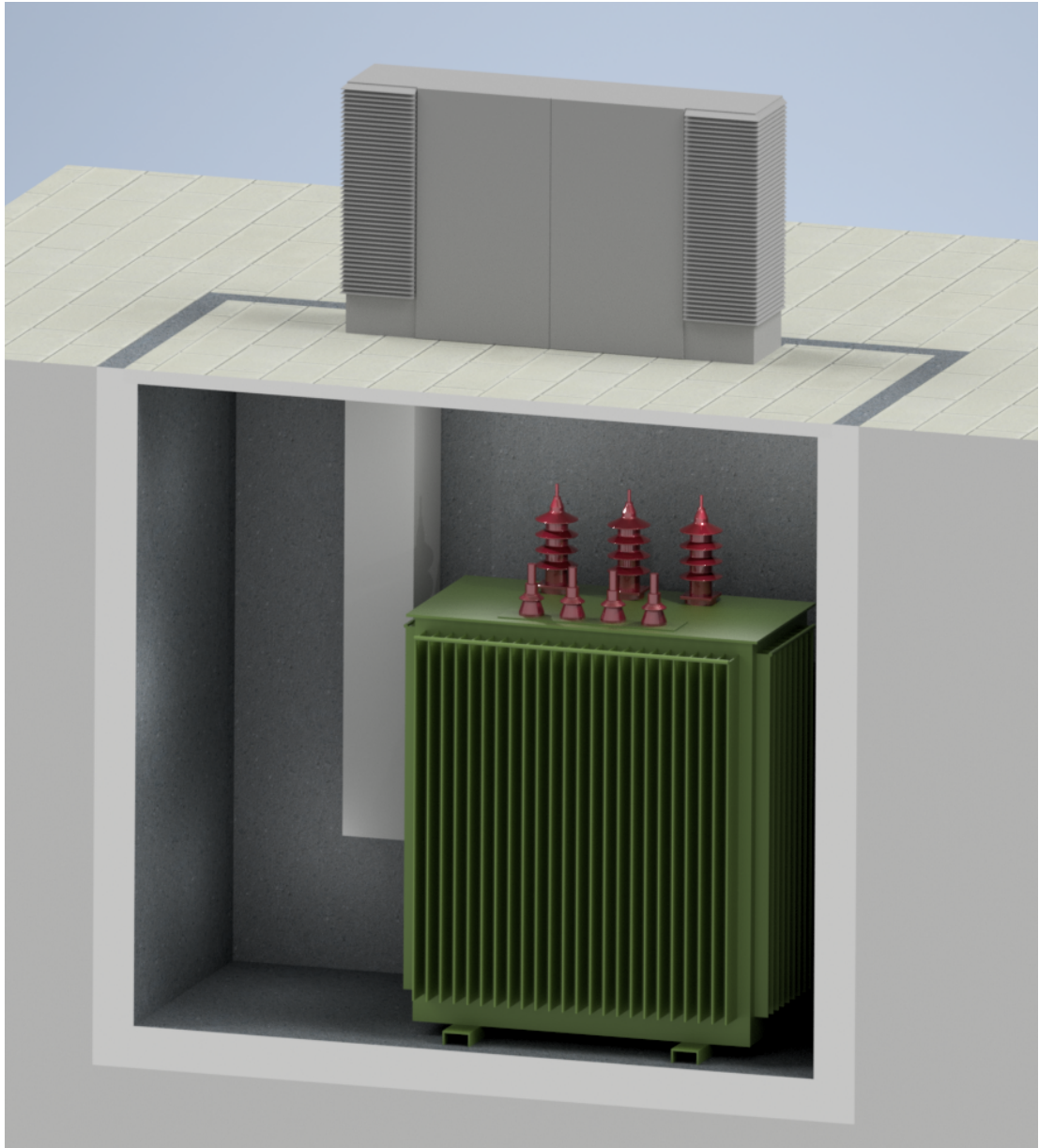


Figure A.1.: Design study for the *Medi* concept, ventilation integrated with distribution cabinet, *cabinet-setup*

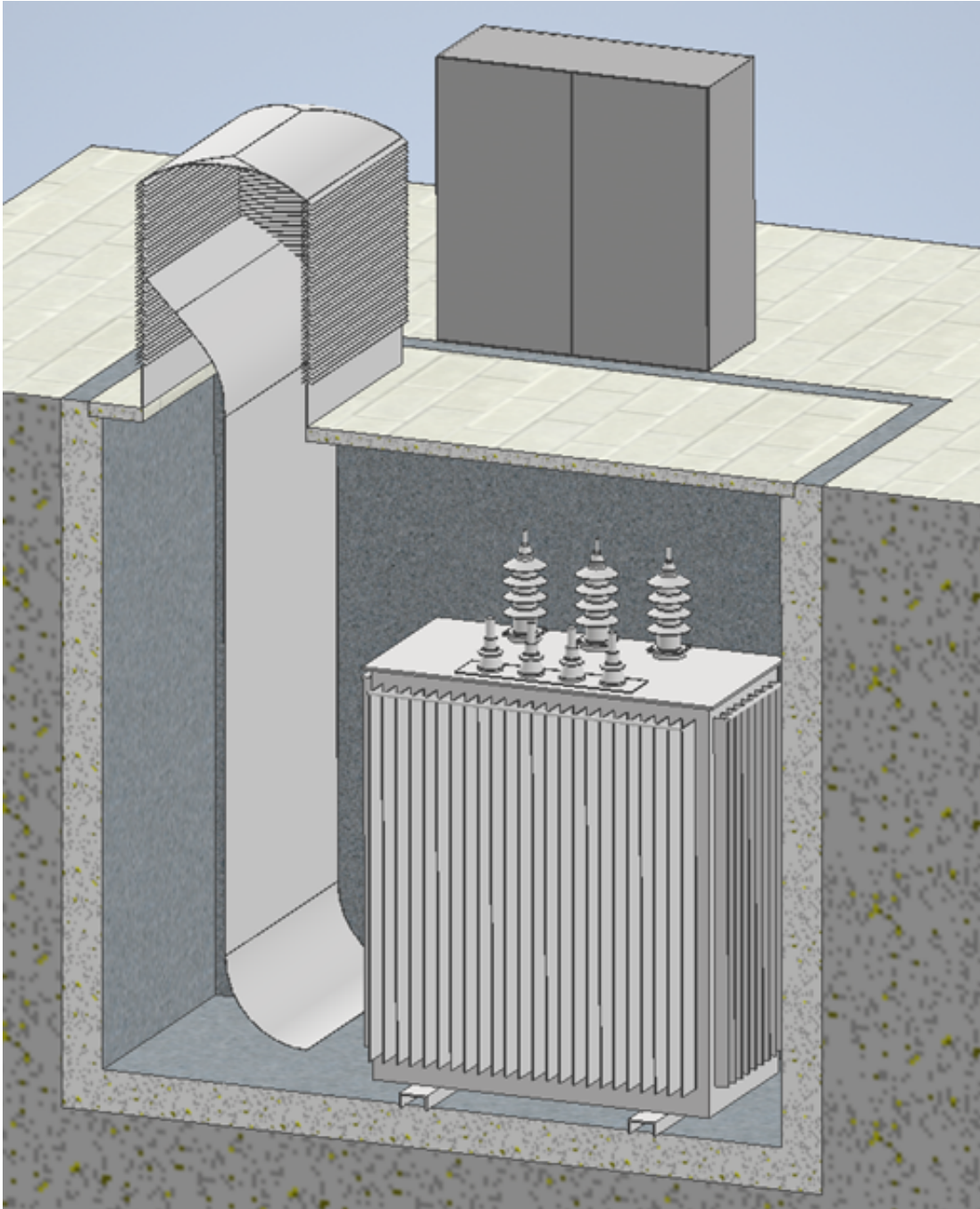


Figure A.2.: Design study for the *Medi* concept, ventilation from a single in-/outlet

Functions	Solutions				
Transformer capacity	50 kV A – 100 kV A	160 kV A – 250 kV A	400 kV A – 630 kV A	800 kV A – 1000 kV A	> 1000 kV A
Depth					 Walk In?
Cooling	Dry	Oil Natural	Oil Forced (Direct)	Air Natural	Air Forced Water Passive Water Forced
Tap changer	On Load	Manual	None		
Vault Material	Reinforced concrete	Concrete	Steel	Aluminium	Reinforced polymer
Grid Topology	Radial	Ring	Subring	Branches	
MV-Cable	Al 630 mm ²	Al 240 mm ²	Al 150 mm ²	Al 95 mm ²	Cu 95 mm ² Cu 50 mm ² Cu 25 mm ²
Transformer connection	Screw Terminals	Elbow connector	Branch cable joint		
MV-protection	Ring main unit off-site	Local fuse	Off-site fuse		
LV-Rails	Few (1-4)	Some (5-8)	Many (9-14)		
Small consumers	FlexOVL	No FlexOVL	None		
Generator terminals	Yes	No			
Telecom	MV-Monitoring	Remote control	LV-Monitoring	None	

Figure A.3.: Morphological chart with eliminated options highlighted in red

Functions	Solutions						
Transformer capacity	50 kVA – 100 kVA	160 kVA – 250 kVA	400 kVA - 630 kVA	800 kVA – 1000 kVA	> 1000 kVA		
Depth							Walk In?
Cooling	Dry	Oil Natural	Oil Forced (Direct)	Air Natural	Air Forced	Water Passive	Water Forced
Tap changer	On Load	Manual	None				
Vault Material	Reinforced concrete	Concrete	Steel	Aluminium	Reinforced polymer		
Grid Topology	Radial	Ring	Subring	Branches			
MV-Cable	Al 630 mm ²	Al 240 mm ²	Al 150 mm ²	Al 95 mm ²	Cu 95 mm ²	Cu 50 mm ²	Cu 25 mm ²
Transformer connection	Screw Terminals	Elbow connector	Branch cable joint				
MV-protection	Ring main unit off-site	Local fuse	Off-site fuse				
LV-Rails	Few (1-4)	Some (5-8)	Many (9-14)				
Small consumers	FlexOVL	No FlexOVL	None				
Generator terminals	Yes	No					
Telecom	MV-Monitoring	Remote control	LV-Monitoring	None			

Figure A.4.: Morphological chart for the mini concept, dark green: chosen options; light green: possible alternatives

Functions	Solutions					
Transformer capacity	50 kV A – 100 kV A	160 kV A – 250 kV A	400 kV A - 630 kV A	800 kV A – 1000 kV A	> 1000 kV A	
Depth					Walk In?	
Cooling	Dry	Oil Natural	Oil Forced (Direct)	Air Natural	Air Forced	Water Passive Water Forced
Tap changer	On Load	Manual	None			
Vault Material	Reinforced concrete	Concrete	Steel	Aluminium	Reinforced polymer	
Grid Topology	Radial	Ring	Subring	Branches		
MV-Cable	Al 630 mm ²	Al 240 mm ²	Al 150 mm ²	Al 95 mm ²	Cu 95 mm ²	Cu 25 mm ²
Transformer connection	Screw Terminals	Elbow connector	Branch cable joint			
MV-protection	Ring main unit off-site	Local fuse	Off-site fuse			
LV-Rails	Few (1-4)	Some (5-8)	Many (9-14)			
Small consumers	FlexOVL	No FlexOVL	None			
Generator terminals	Yes	No				
Telecom	MV-Monitoring	Remote control	LV-Monitoring	None		

Figure A.5.: Morphological chart for the Medi concept

Functions	Solutions						
Transformer capacity	50 kVA – 100 kVA	160 kVA – 250 kVA	400 kVA - 630 kVA	800 kV/A – 1000 kV/A	> 1000 kVA		
Depth						Walk In?	
Cooling	Dry	Oil Natural	Oil Forced (Direct)	Air Natural	Air Forced	Water Passive	Water Forced
Tap changer	On Load	Manual	None				
Vault Material	Reinforced concrete	Concrete	Steel	Aluminium	Reinforced polymer		
Grid Topology	Radial	Ring	Subring	Branches			
MV-Cable	Al 630 mm²	Al 240 mm²	Al 150 mm²	Al 95 mm²	Cu 95 mm²	Cu 50 mm²	Cu 25 mm²
Transformer connection	Screw Terminals	Elbow connector	Branch cable joint				
MV-protection	Ring main unit off-site	Local fuse	Off-site fuse				
LV-Rails	Few (1-4)	Some (5-8)	Many (9-14)				
Small consumers	FlexOVL	No FlexOVL	None				
Generator terminals	Yes	No					
Telecom	MV-Monitoring	Remote control	LV-Monitoring	None			

Figure A.6.: Morphological chart for the maxi concept

All-electric / warmtepompen					
Transformatorvermogen (bij warmtepompen)					
Bij plaatsing van een nieuwe transformator of het vervangen van het LS-rek of de MS-installatie, moet worden ingeschat welke transformator leidt tot een lokaal toekomstvast ontwerp. Het maximaal aantal klanten uit onderstaande tabel kan worden gebruikt als vuistregel.					
Transformer	Unknown/Mixed	Apartments	Terraced Housing	Semi-detached	Detached
	Onbekend / gemixed	Appartementen +cvz	Tussen- en hoekwoningen	2-onder-1-kap-woningen	vrijstaande woningen
100kVA-transformator	10	14	12	8	7
250kVA-transformator	30	42	36	26	22
400kVA-transformator	52	70	60	46	37
630kVA-transformator	87	115	100	77	62
1000kVA-transformator	145	189	175	129	103

Figure A.7.: Estimate number of housing connections per transformer and residence type. Rule of thumb for use pre-grid calculation.

B. Temperature dependent material properties of Transformer Oil

Shown below are the temperature dependent material properties of the transformer oil material used by COMSOL. Plots exported from COMSOL's material database.

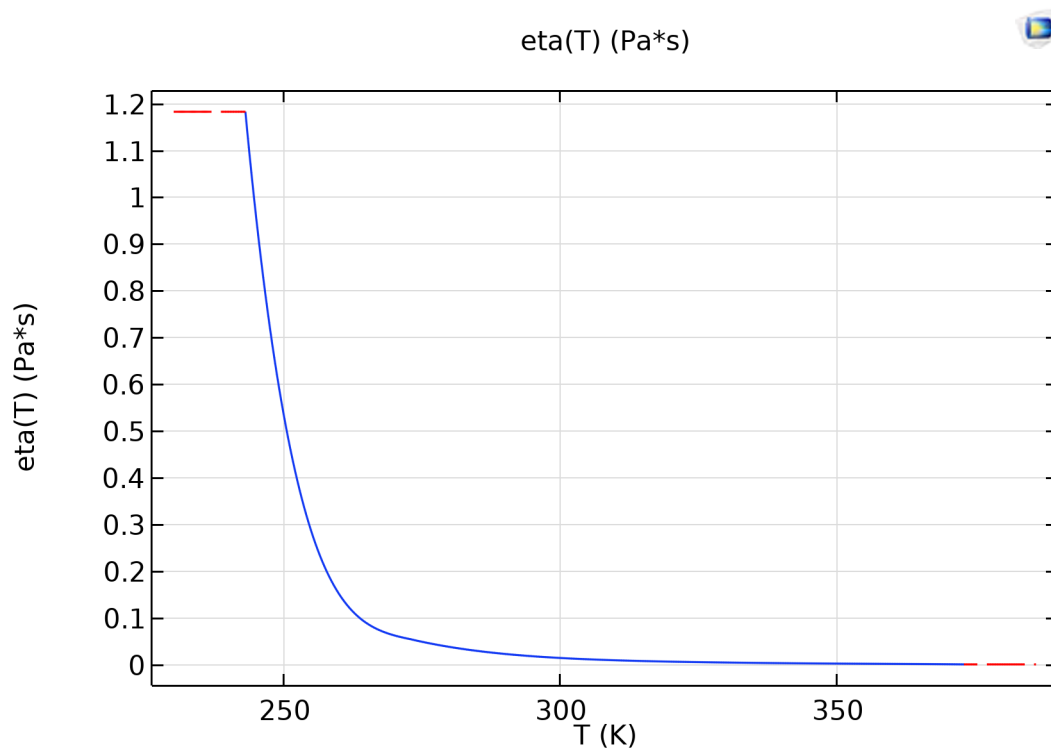


Figure B.1.: Dynamic Viscosity

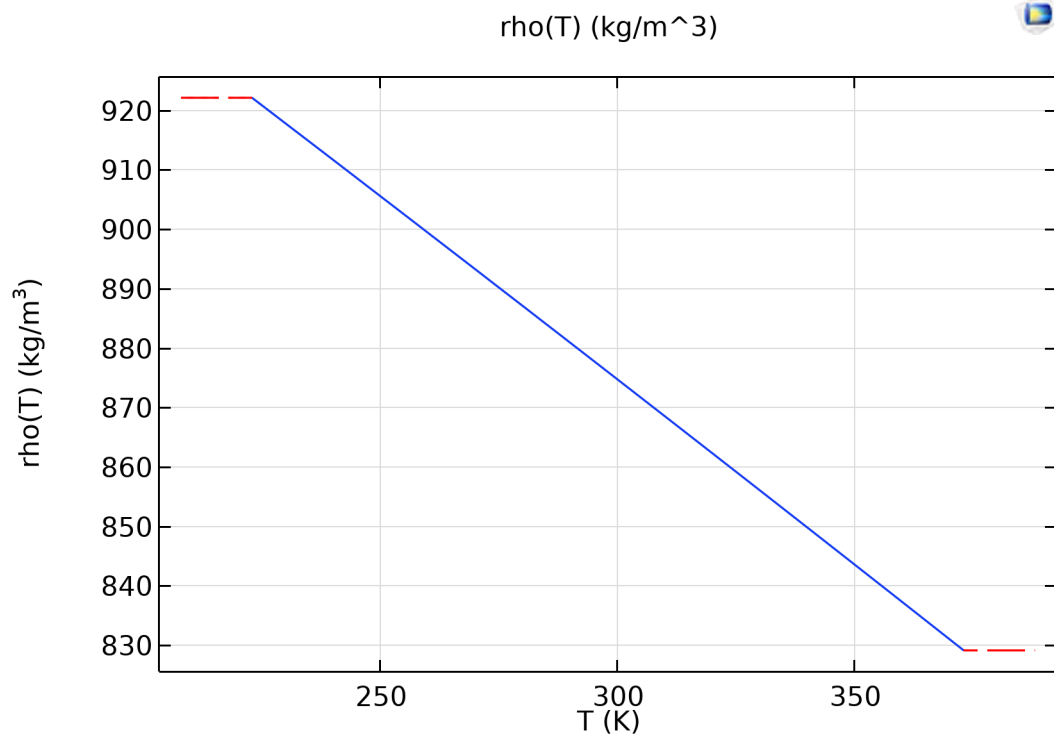


Figure B.2.: Density

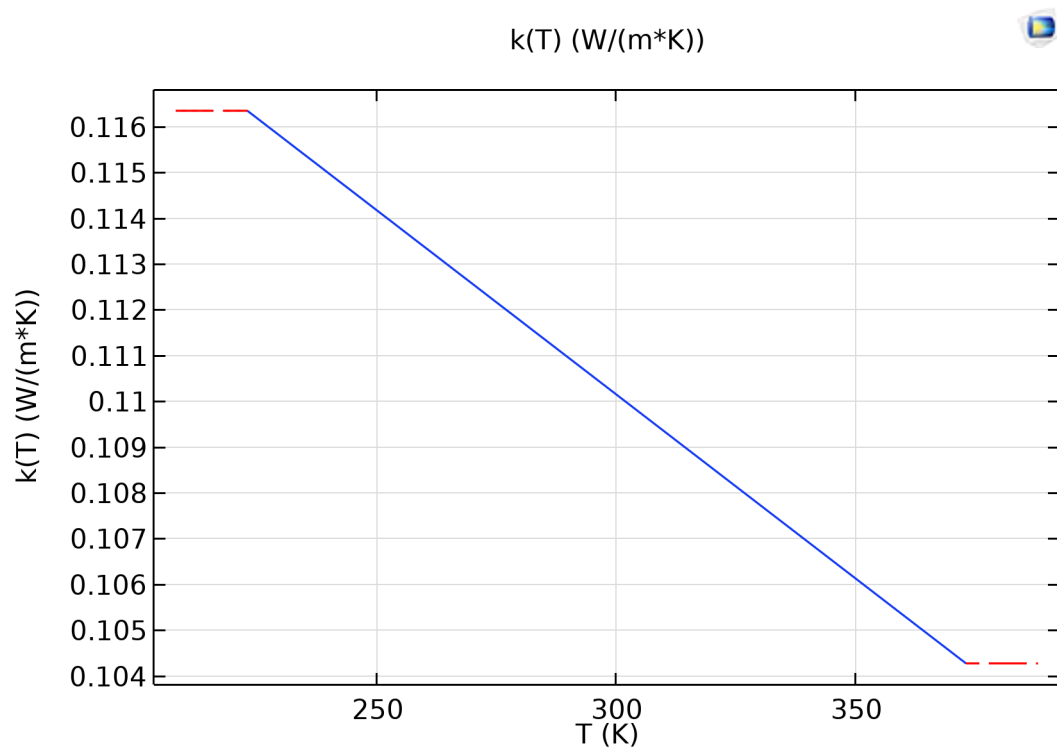


Figure B.3.: Thermal Conductivity

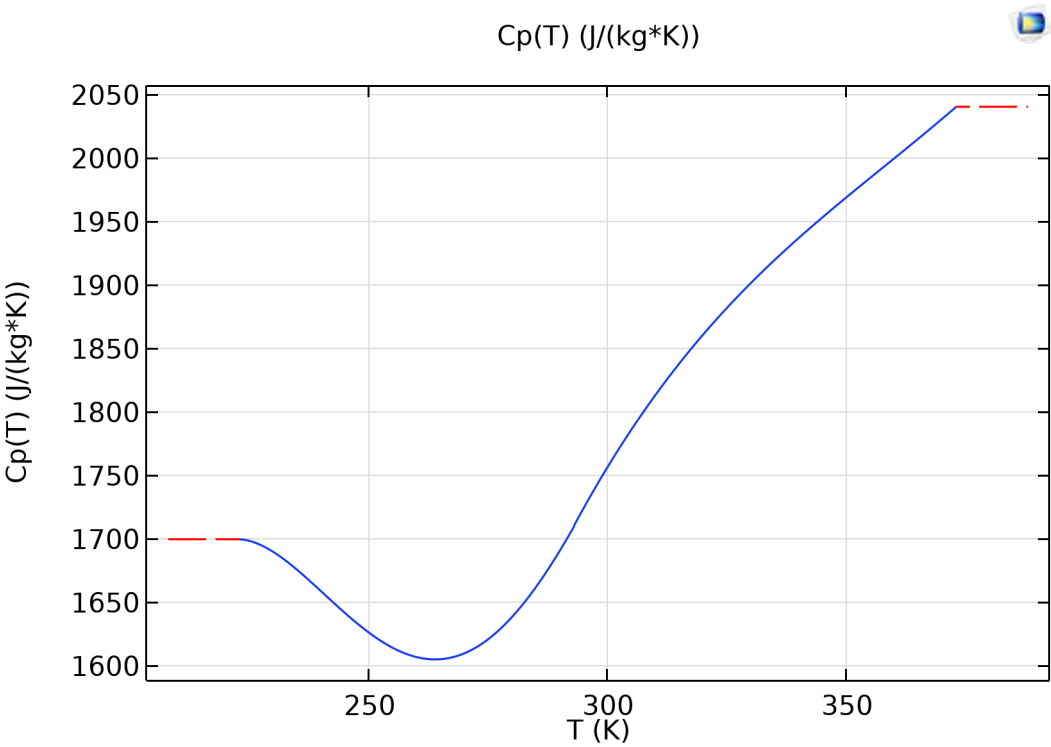


Figure B.4.: Specific Heat

C. Evaluation of the Boussinesq approximation

Three simulations were performed to compare the effects of the Boussinesq approximation on the *fin-slice* model. The boundary conditions are as described in Chapter 4.2, with the following adaptations, for detailed description of formulas evaluated see COMSOL CFD User Guide [59]:

1. Incompressible flow with gravity, Boussinesq approximation with a reference temperature of 293 K (same as model in 4.2)
2. Incompressible flow with gravity, Boussinesq approximation with a reference temperature of 348 K, corresponding to a top oil temperature of approx 74 °C
3. Flow regime set to weakly compressible flow with gravity.

Temperature results of select locations, shown in Figure C.1 were recorded, as well as the computational time of the different models.

Table C.1.: Comparison of different flow regimes

	Bous. @ 293 K	Bous. @ 348 K	No Bous.
$T_{\text{avg,Bot}}$ [°C]	43.54	50.33	48.82
$T_{\text{avg,Lid}}$ [°C]	72.58	70.72	70.82
$T_{\text{avg,TopOil}}$ [°C]	80.75	74.97	75.29
Calc. Time [h]	4.8	31.6	12.2

It can be seen that for simulations where the kinematic viscosity is lower (as in 348 K), or dependent on temperature (as in No Bous.), the hot areas of the model (lid and top oil) are approx. 2 – 5 K cooler, while the temperatures on the underside (Bot.) are 5 – 8 K warmer. This effect can be explained by the decreased kinematic viscosity of the oil (see Fig. C.2), resulting in higher flow velocities, and therefore a more efficient heat transport (lower peak temperature), as well as a lower temperature gradient from the top to bottom of the transformer, due to the faster flow and better mixing at lower viscosities, see Fig. C.3. Computational times of the 293 K model were significantly shorter than for the other two modes.

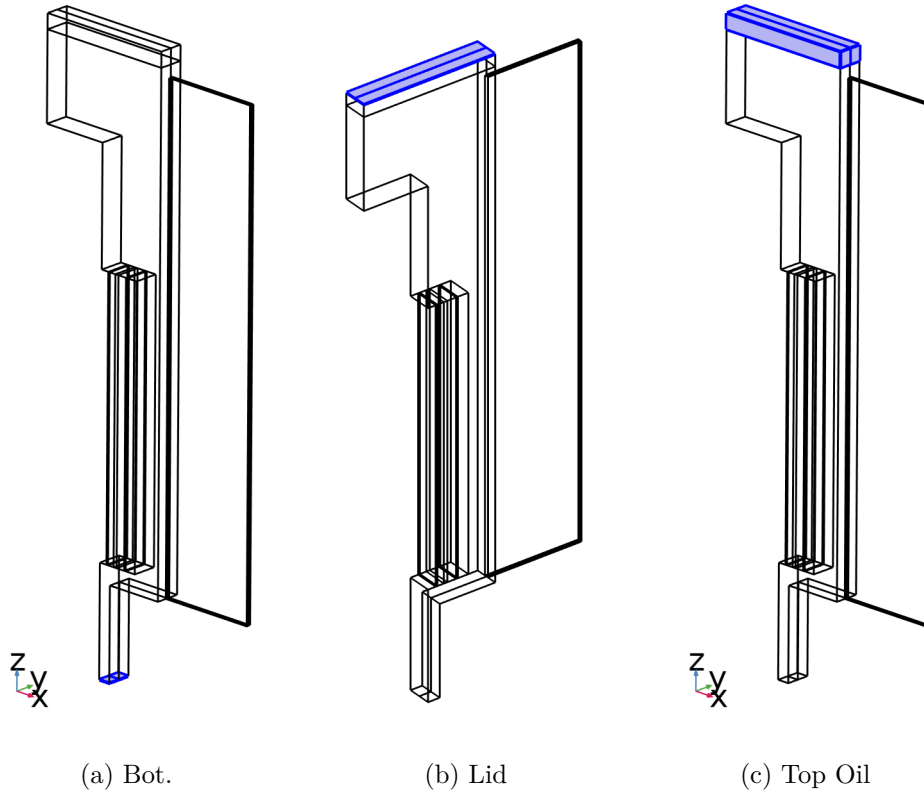


Figure C.1.: Locations of the defined average temperatures from Table C.1

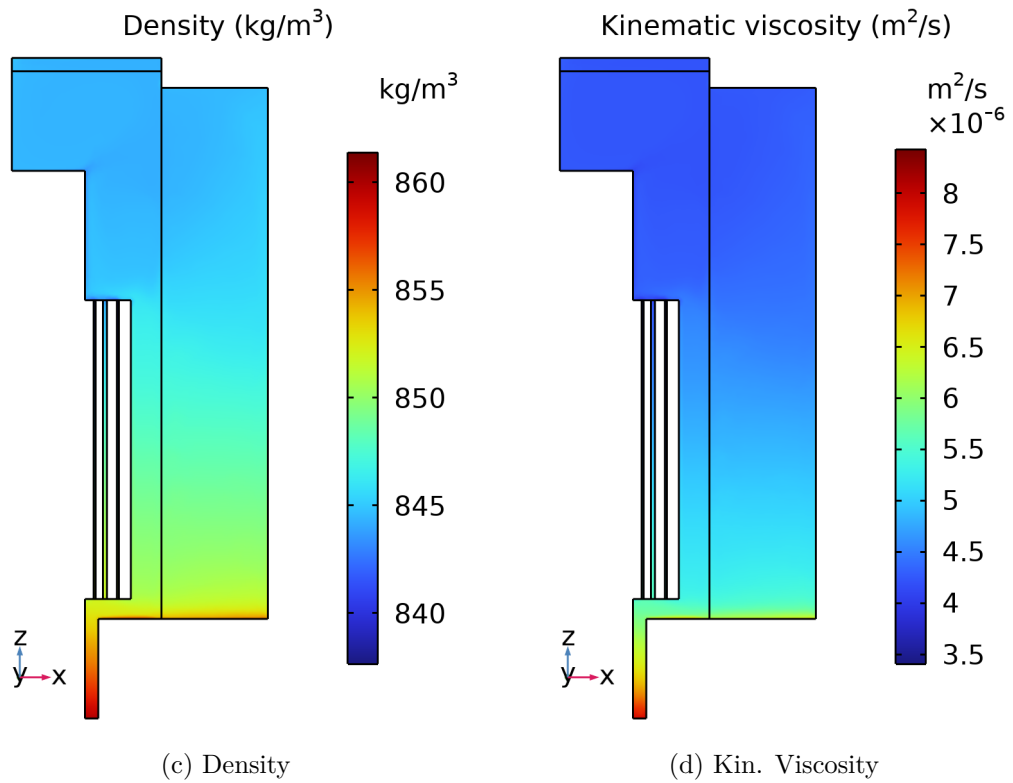
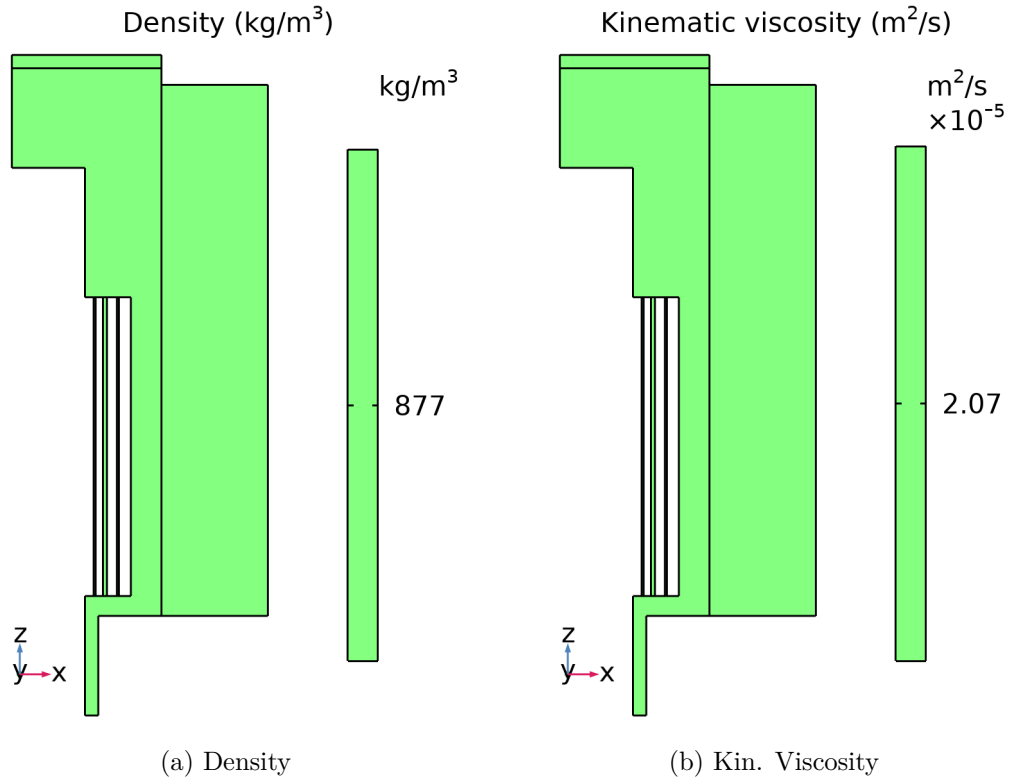


Figure C.2.: Material properties at steady state: (a-b) assuming the Boussinesq approximation; (c-d) assuming weakly compressible flow, variations of mat. properties with temperature visible when Boussinesq approx. is not applied.

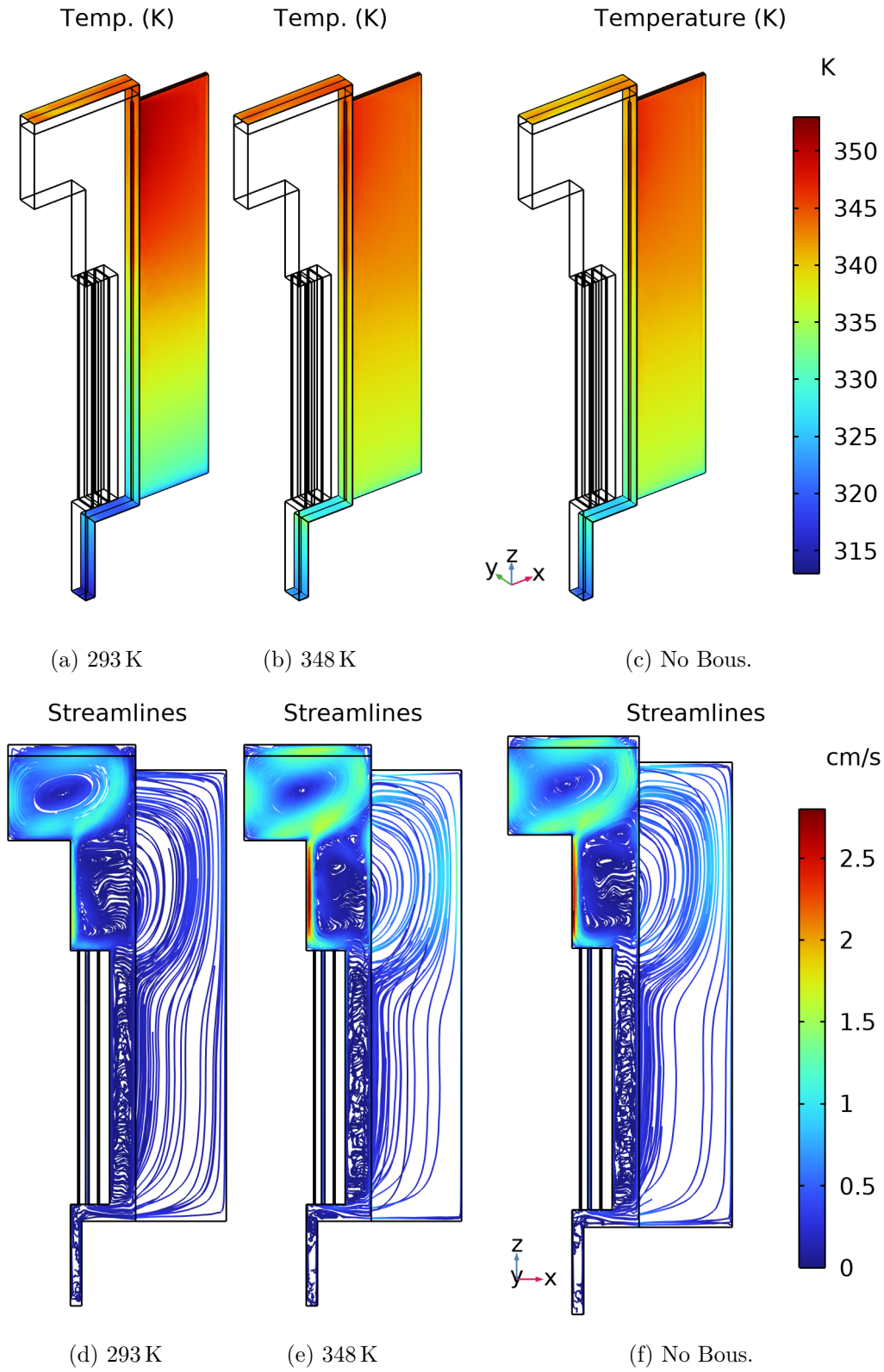


Figure C.3.: (a-c): Surface temperatures [K]; (d-f): Streamlines coloured by flow velocity [cm/s], taken at steady state

D. COMSOL Figures

Geometric features, materials, and boundary conditions applied to the *box-setup* model in COMSOL. Akin to those described for the *cabinet-setup* in Chapter 4.

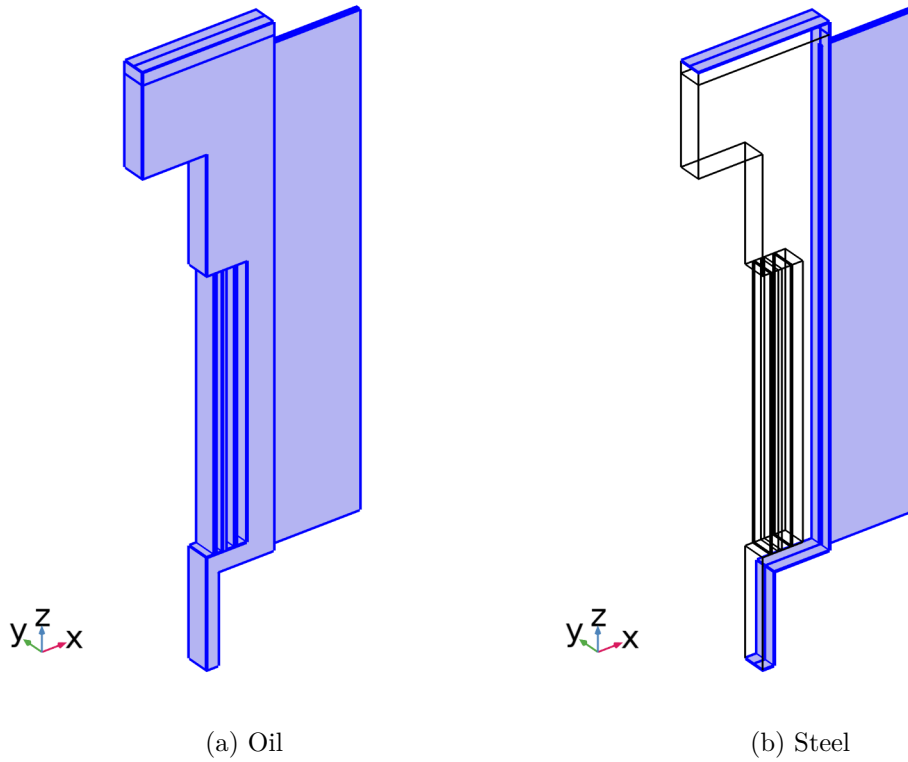


Figure D.1.: Material assignments in the *fin-slice* model. From Section 4.2.1.

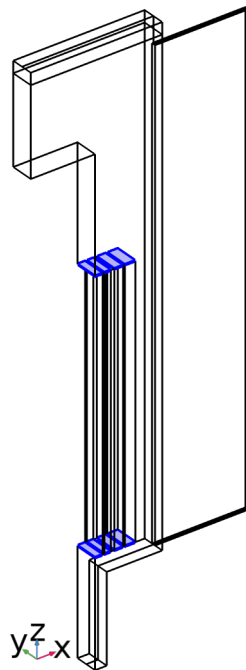
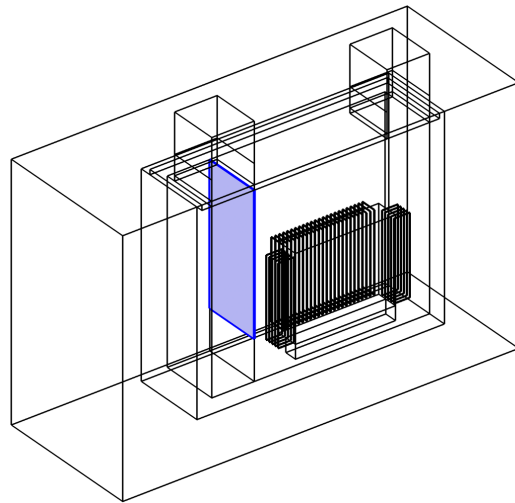
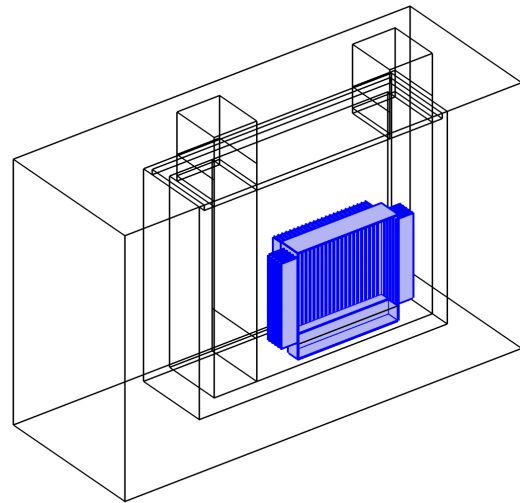


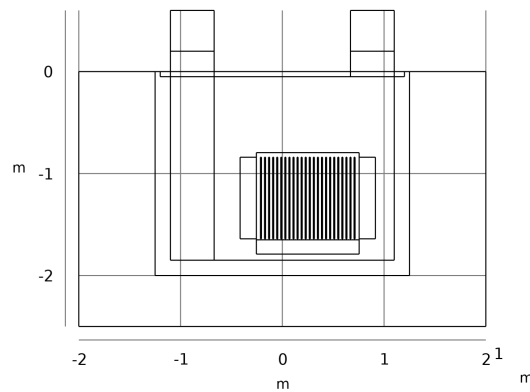
Figure D.2.: Thermal insulation boundaries



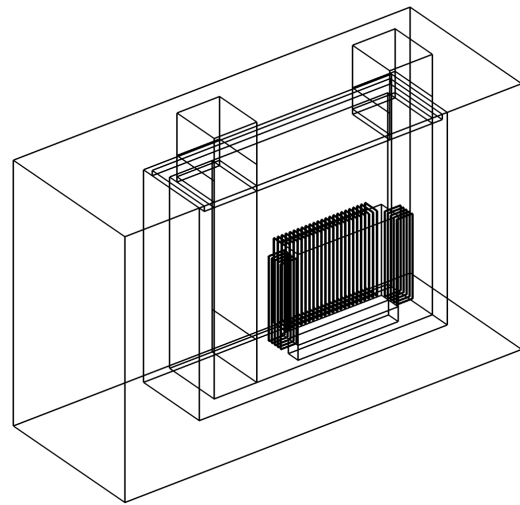
(a) Location of the flow guard in the domain



(b) Simplified transformer



(c) Side view



(d) Half-Box Domain

Figure D.3.: Different features of the 3D models in COMSOL

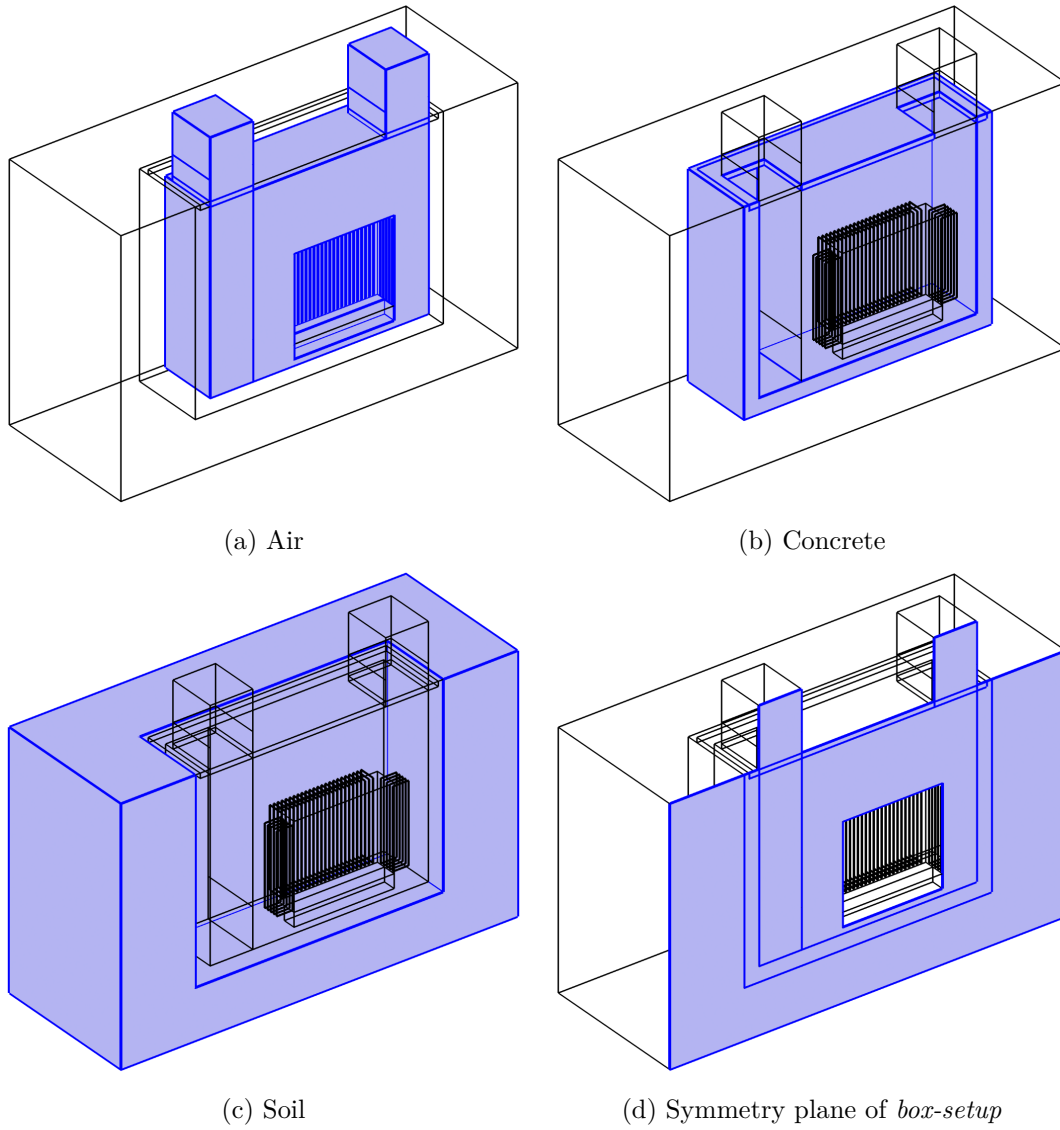
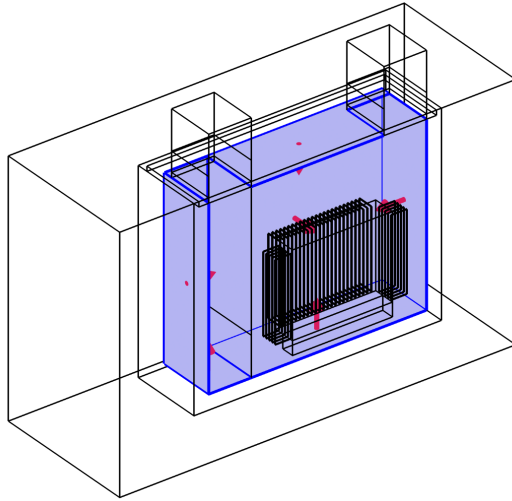
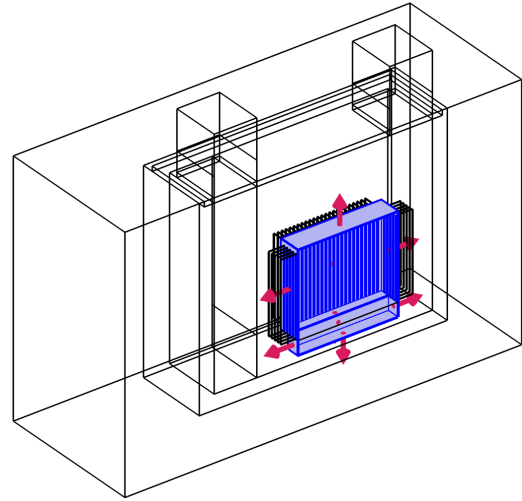


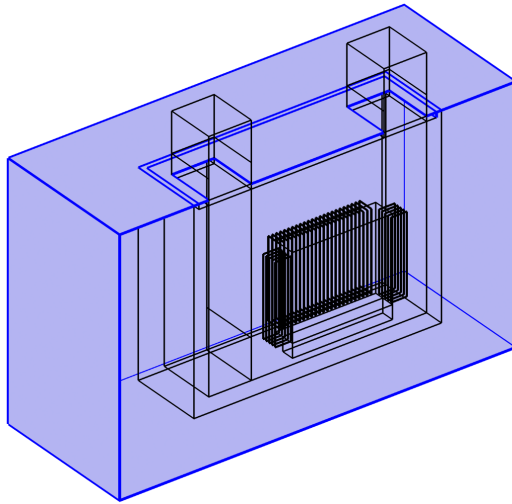
Figure D.4.: Material assignments and symmetry plane in COMSOL



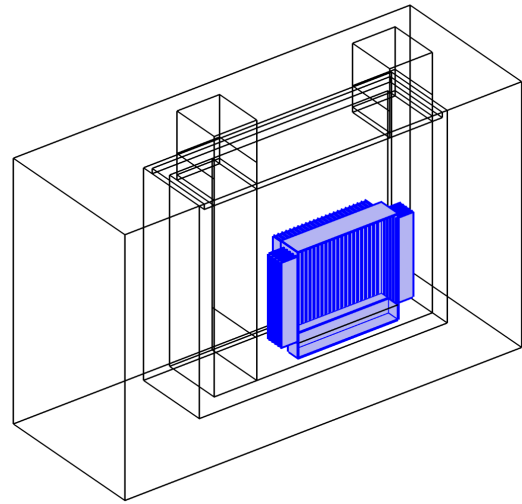
(a) Radiation domain outer walls



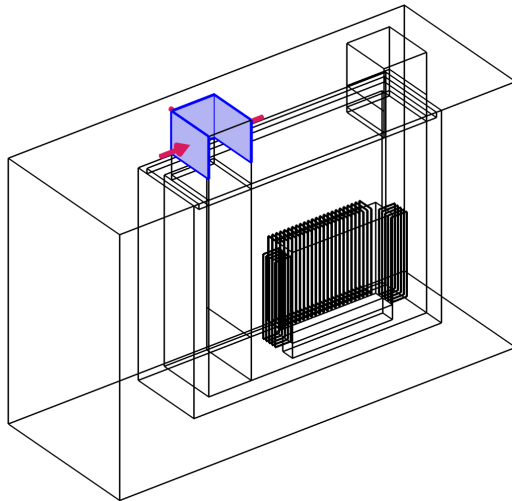
(b) Radiation boundaries on the transformer



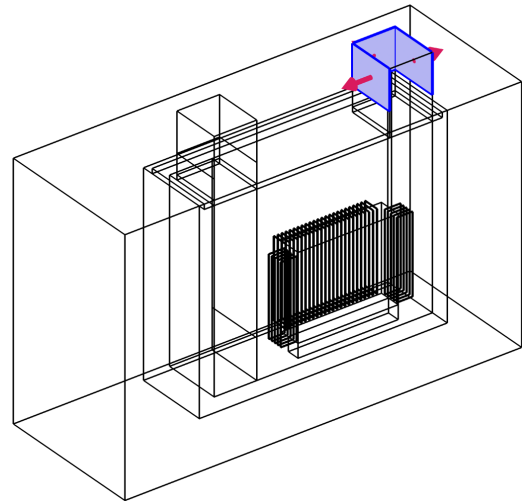
(c) Ambient Temperature



(d) Transformer temperature



(e) Inlet



(f) Outlet

Figure D.5.: Radiative and thermal boundaries assigned to the *cabinet-setup*

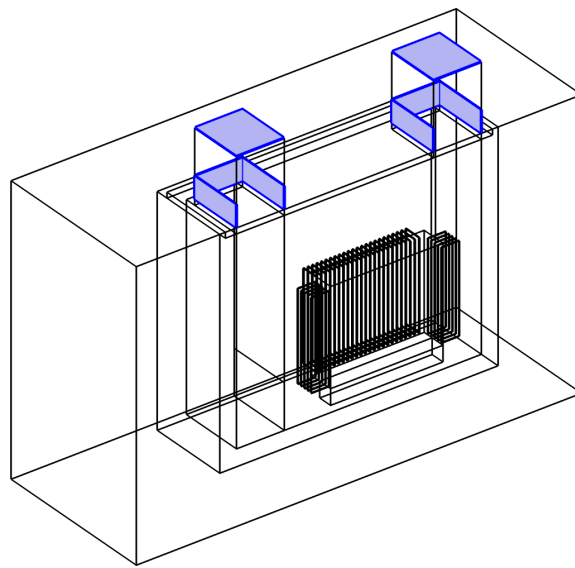


Figure D.6.: Thermal insulation boundaries on the box setup.

E. Mesh Settings and Study

Automatically generated meshes in COMSOL are labelled with the setting used in COMSOL. The manual mesh was first generated as a extra coarse mesh. It was then refined by applying a swept hexahedral mesh to the fin, and the cooling channels. Once the basic mesh was generated, *boundary layer* elements were generated on boundaries that function as walls. Due to the long solving times of the manual mesh it was not further used in the study.

The meshes used for the vault simulations were all automatically generated, and akin to the *fin-slice* model were composed of different element types, as well as having *boundary layer* elements generated on (interior)-walls.

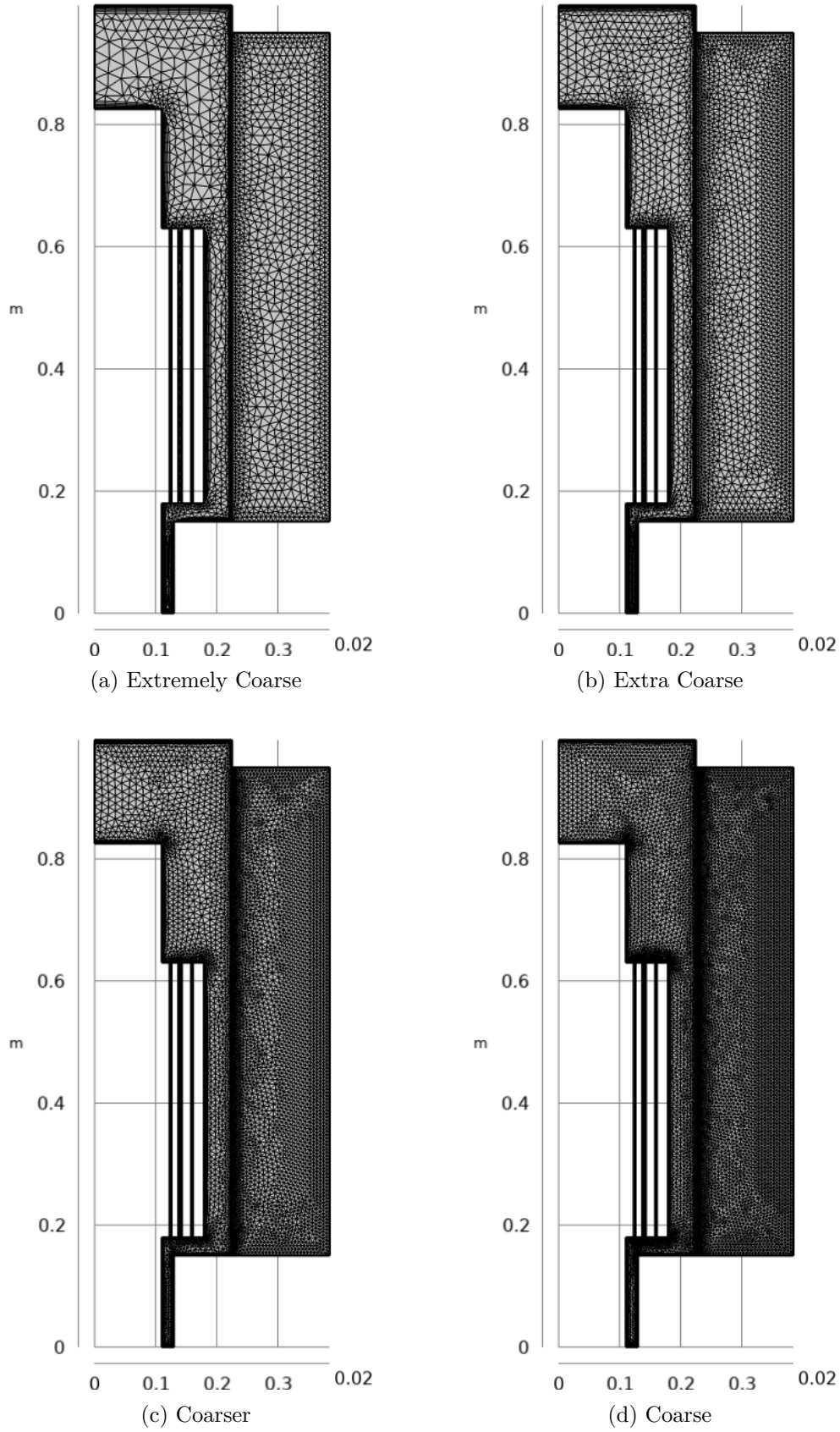


Figure E.1.: Generated meshes *fin-slice*.

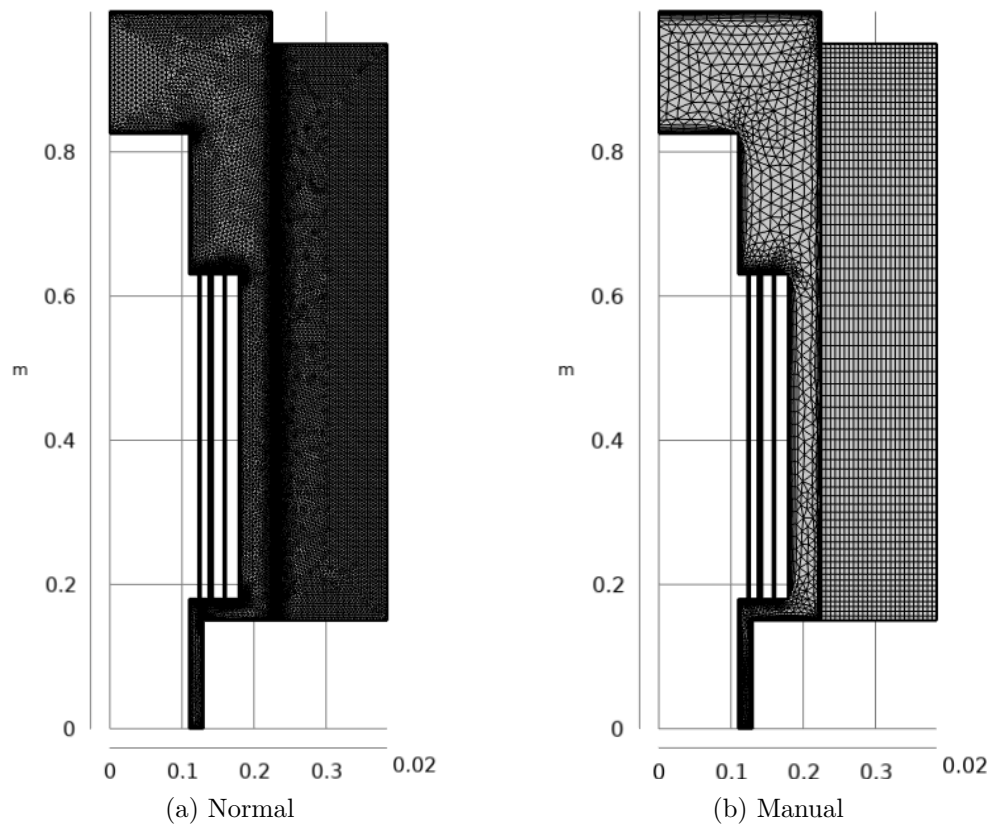


Figure E.2.: Generated meshes *fin-slice*.

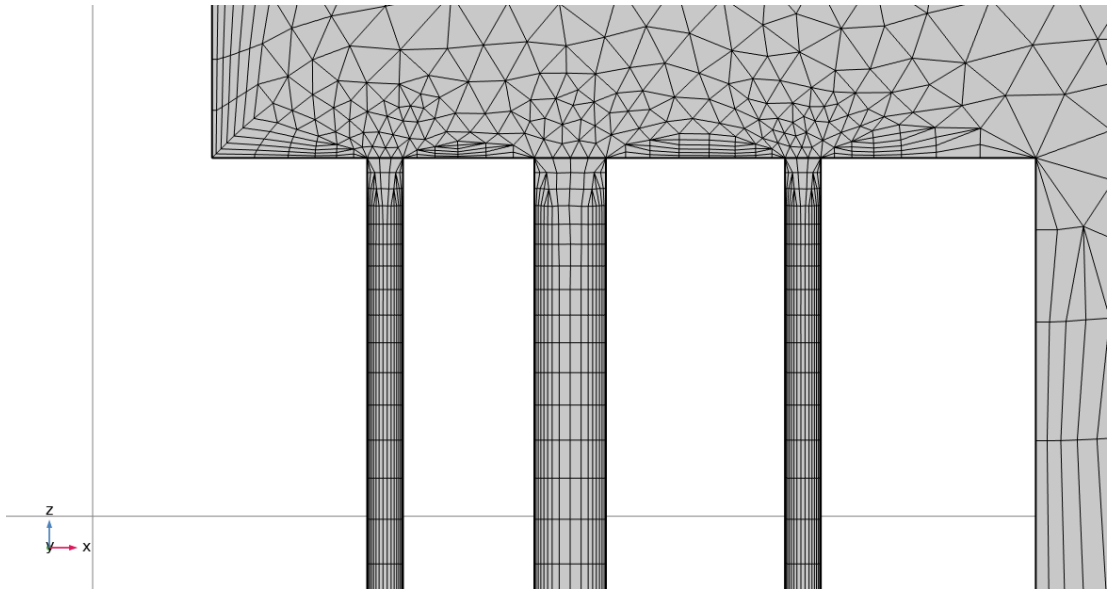


Figure E.3.: Detail of the generated manual mesh for the cooling channels.

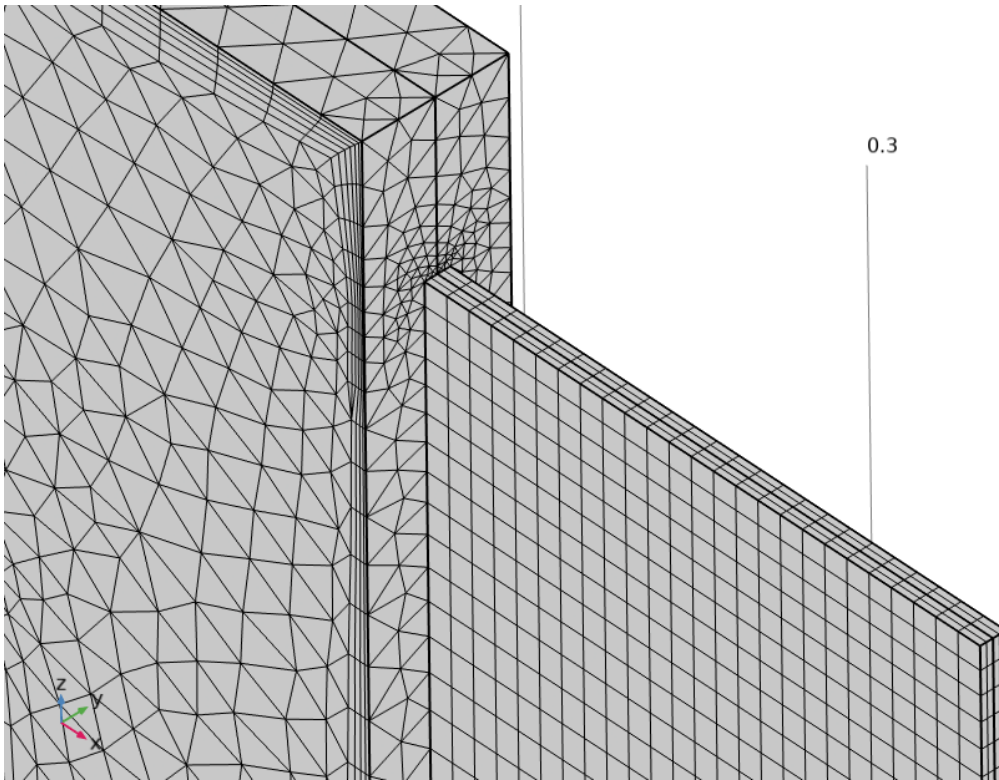


Figure E.4.: Detail of the generated manual mesh on the fin.

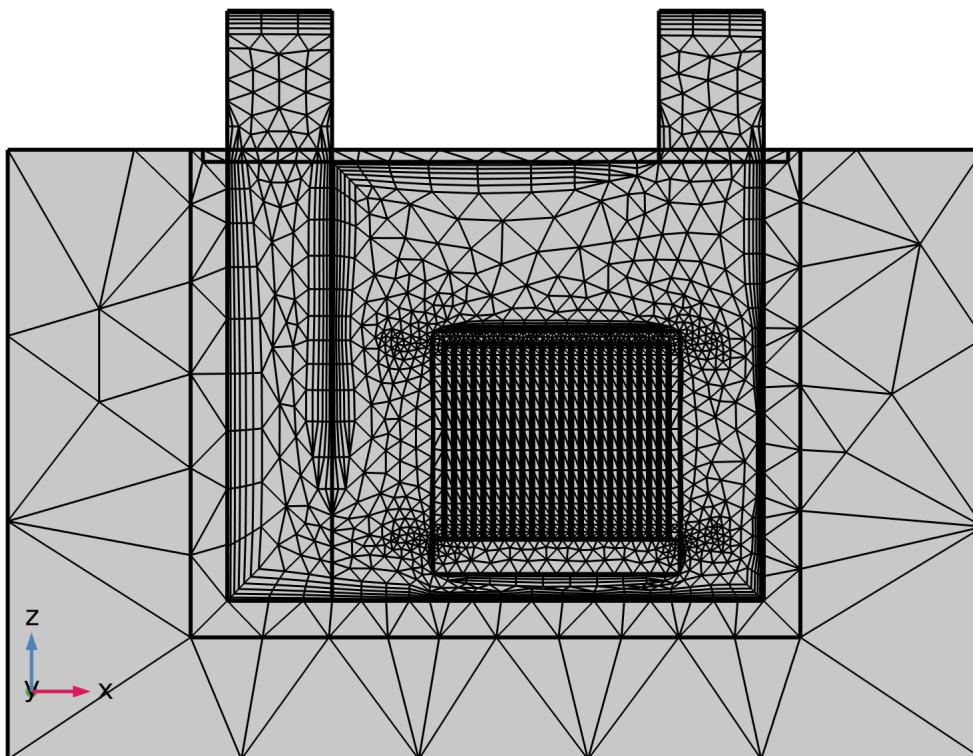


Figure E.5.: *Box-setup* Extremely Coarse

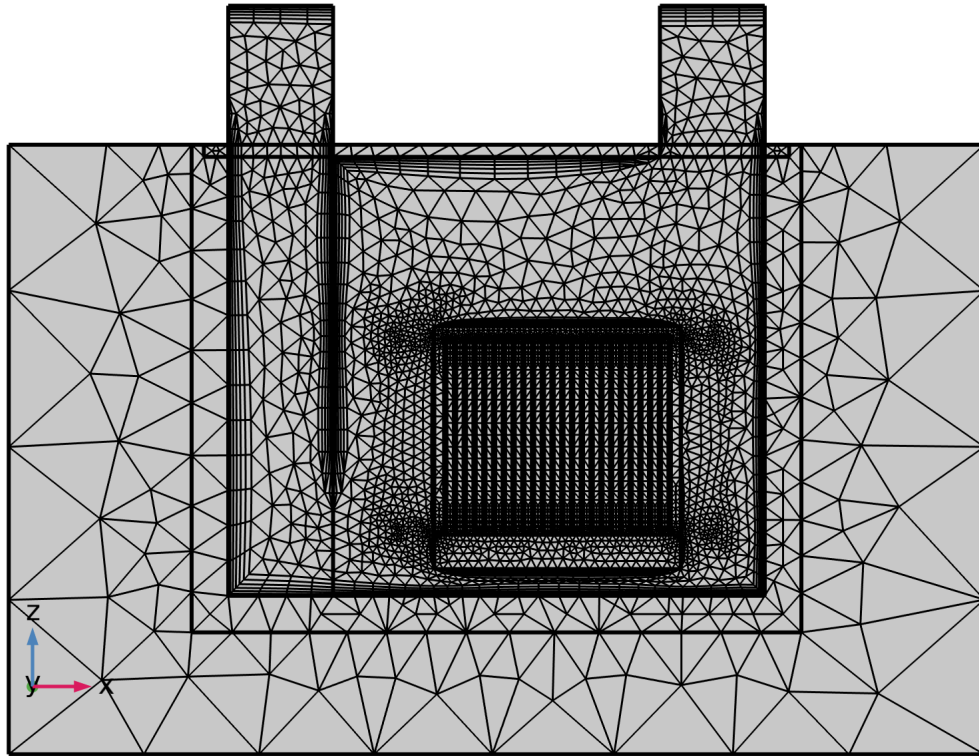


Figure E.6.: *Box-setup* Coarser

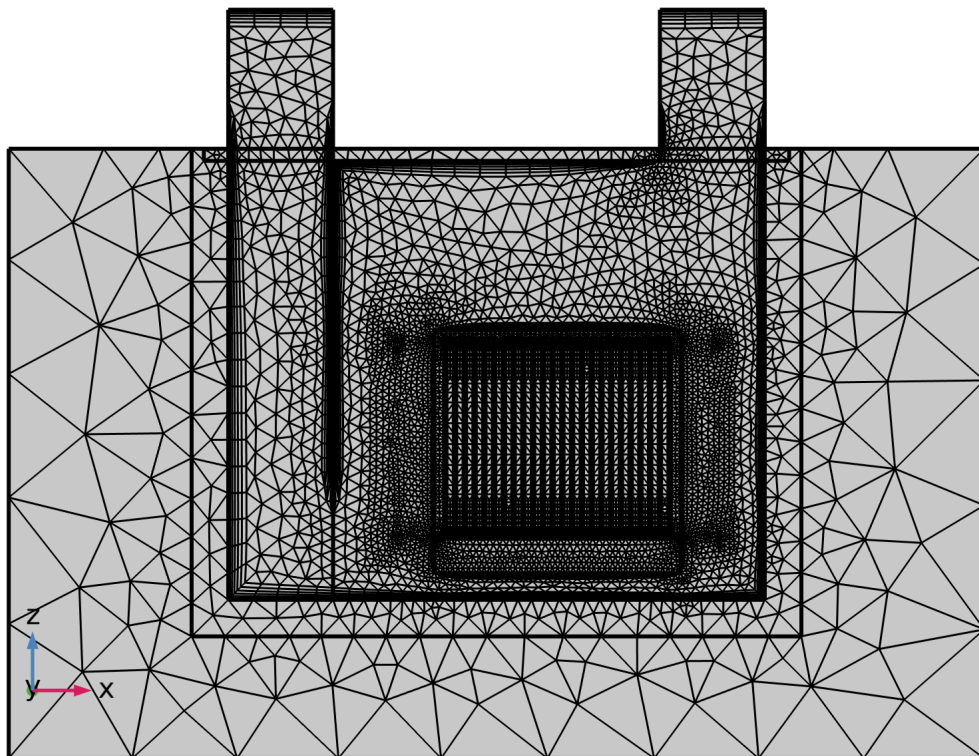
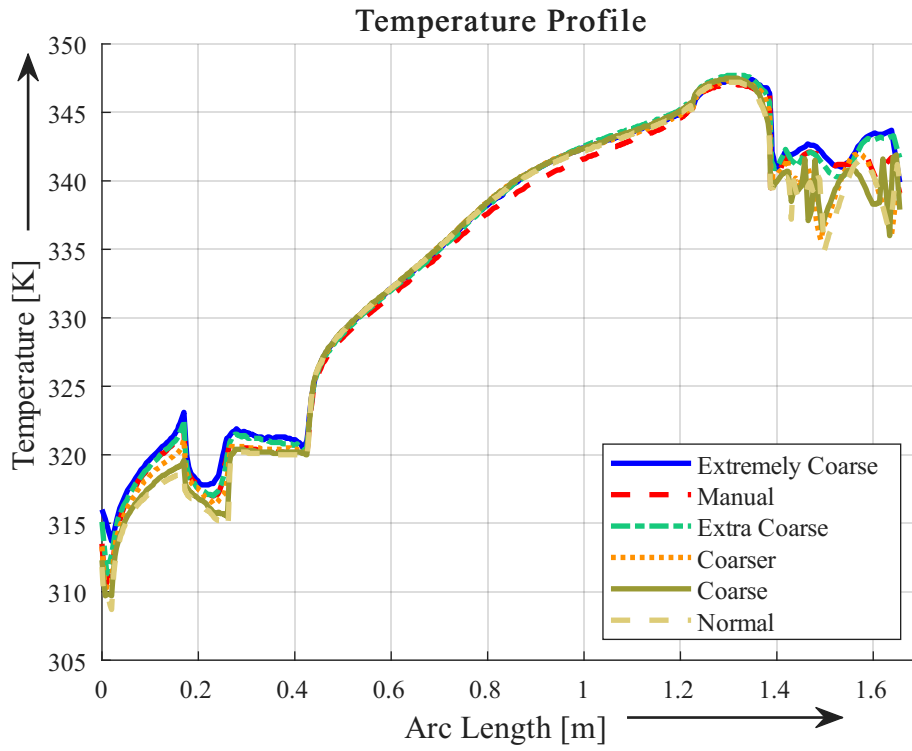
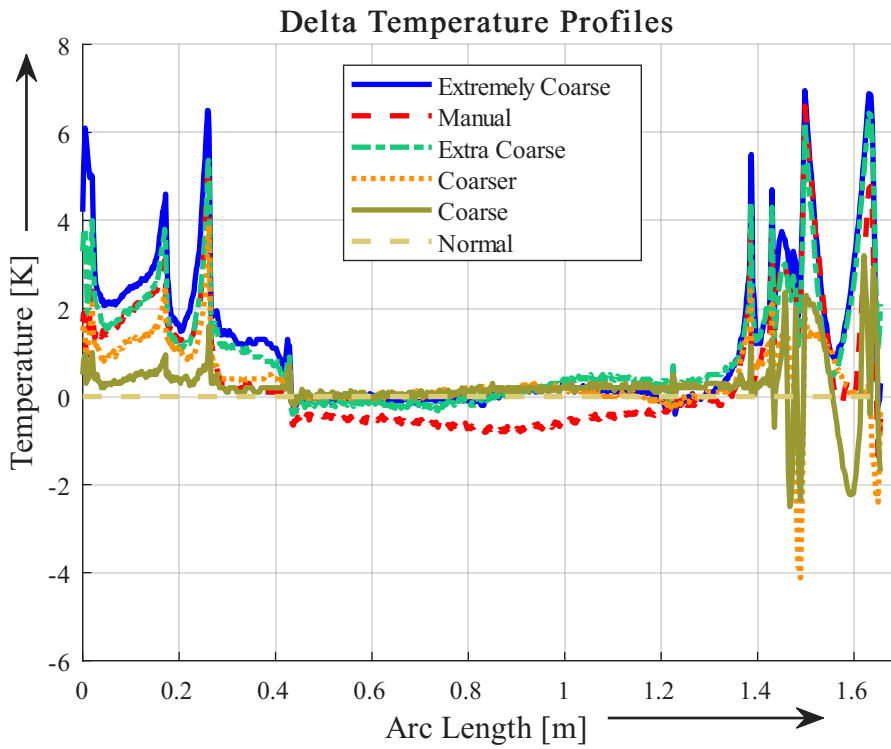


Figure E.7.: *Box-setup* Coarse



(a) Temperature profile arc length.



(b) Delta of temperature profile arc length. *Normal* profile taken as reference.

Figure E.8.: Temperature profile comparison along the arc length for the different meshes.

F. Ventilation Area Calculation

The equation to calculate the desired enclosure class of an indoor substation, where the height difference was adjusted to meet the geometry of this study is:

$$A_{\text{in-outlet}} = \frac{P_{\text{Transformer}} \sqrt{K}}{219 \sqrt{\Delta h_{\text{thermal}} (K_{\text{Enclosure}} + 13)^3}} \quad (\text{F.1})$$

Where $A_{\text{in-outlet}}$ is the area of the in- or outlet, $P_{\text{Transformer}}$ the energy dissipated as heat by the transformer in Watts, K the dimensionless loss coefficient of the ventilation, $\Delta h_{\text{thermal}}$ the height difference (z-axis) between the centre of the inlet and the centre of the flow guards opening in meters and $K_{\text{Enclosure}}$ the desired enclosure temperature class according to IEC 62271-202 [69]. Equation taken from Liander specification S3505 *PvE in pandige MSR* (specifications of indoor distribution substations). Calculated using: $P_{\text{Transformer}} = 5140 \text{ W}$, $\Delta h_{\text{thermal}} = 1.8 \text{ m}$, $K = 70$, $K_{\text{Enclosure}} = 20$. Resulting in an in-/outlet area of approx. 0.8 m^2 .

G. Transformer Nameplate

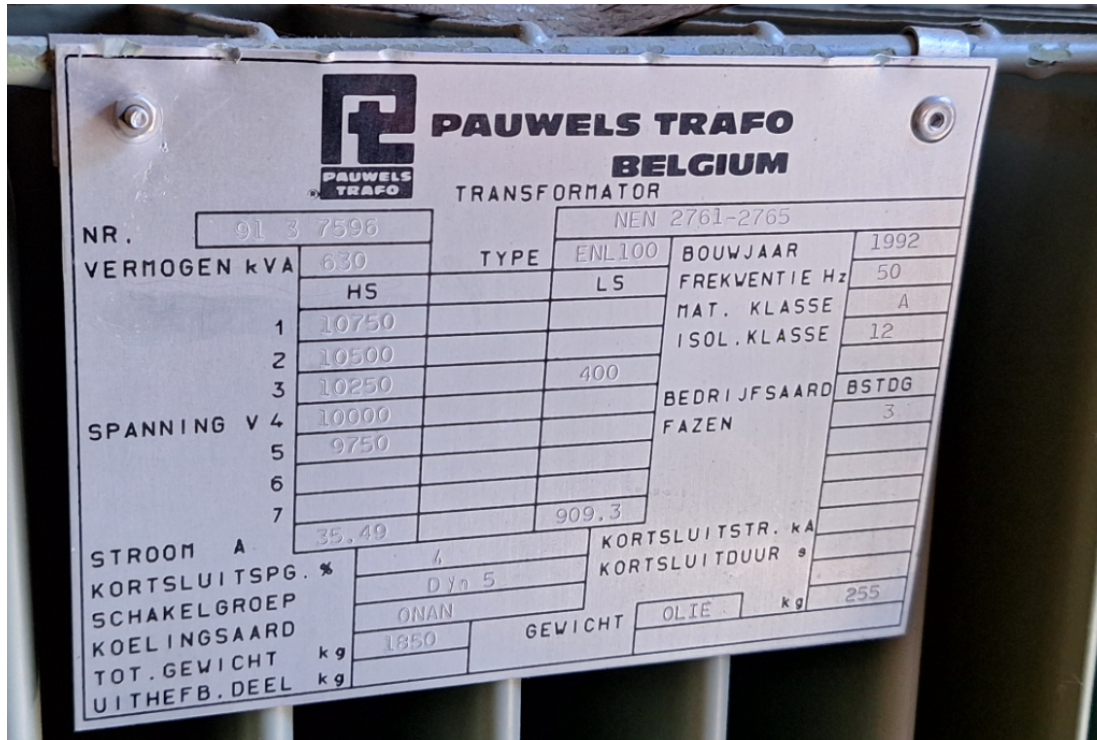


Figure G.1.: Nameplate of the Pauwels 630 kVA distribution transformer

H. Transformer Testing

Additional information regarding the laboratory test of the transformer and vault setups.

Qirion 560KVA Mobile High voltage test Laboratory 2026

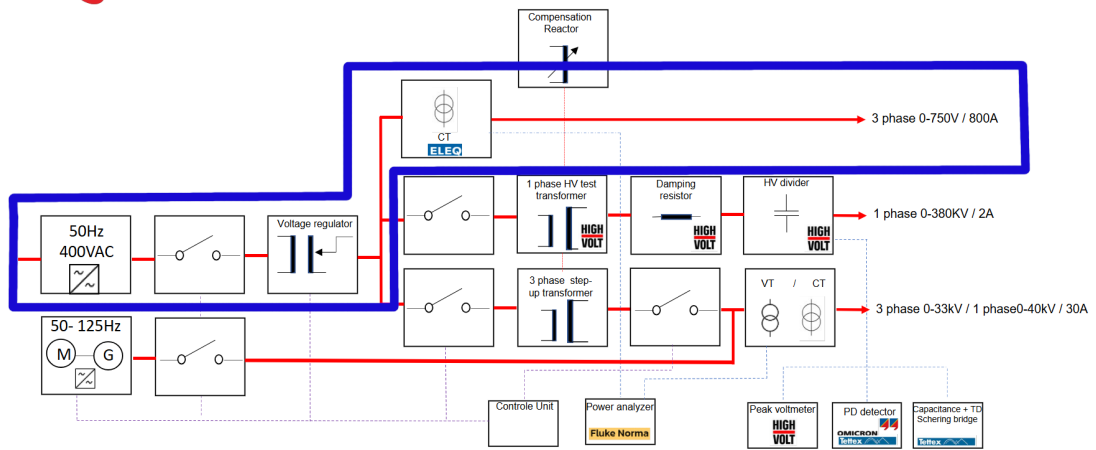


Figure H.1.: Qirion Power Source. Blue box highlights the used output.

H.1. Sensor Values of Temperature Rise Testing at termination

Sensor Nr. 2 "L1 - 2 Fin Top" came lose during testing of Vault 2 due to adhesive failure and is therefore no longer representative.

Table H.1.: Temperature Values at end of Temperature Rise Test

Sensors		Temperatures [°C]		
Number	Logger - Chanel - Name	Free	Vault 1	Vault 2
1	L1 - 1 Top Oil	77.3	89.8	93.9
2	L1 - 2 Fin Top	75.5	88.0	(65.6)
3	L1 - 3 Fin Mid. Upper	66.7	77.7	85.5
4	L1 - 4 Fin Mid. Lower	61.6	73.3	72.6
5	L1 - 5 Fin Bot.	55.7	65.0	66.5
6	L1 - 6 Tank Bot.	38.8	47.1	49.2
7	L1 - 7 Fin Top	75.8	88.5	92.6
8	L1 - 8 Fin Mid. Upper	63.0	77.8	83.8
9	L1 - 9 Fin Mid. Lower	58.5	69.8	73.5
10	L1 - 10 Fin Bot.	53.8	63.9	68.1
11	L1 - 11 Tank Bot.	41.4	48.5	49.4
12	L1 - 12 Lid Center	68.2	84.7	88.8
13	L2 - 1 Tank Mid. Long	71.6	82.7	86.8
14	L2 - 2 Fin Return Long	51.4	59.2	60.0
15	L2 - 3 Tank Mid. Short	72.2	83.1	85.7
16	L2 - 4 Fin Return Short	49.9	58.4	60.3
17	L2 - 5 Lid 3/4 Long	63.9	85.0	89.0
18	L2 - 6 Lid 3/4 Short	66.8	85.2	89.5
19	L2 - 7 Air Vault Top	-	60.9	65.7
20	L2 - 8 Air Vault Mid.	-	46.3	57.5
21	L2 - 9 Air Vault Bot.	-	32.1	33.0
22	L2 - 10 Air Inlet	-	25.3	24.1
23	L2 - 11 Air Outlet	-	63.5	66.5
24	L3 - 1 Ambient Air	23.9	23.7	23.4
25	L3 - 2 Ambient Air	24.1	24.2	23.6
26	L3 - 3 Ambient Air	23.6	23.8	23.2
27	L3 - 4 Ambient Air	24.4	24.2	23.6

Table H.2.: Air velocities at end of Temperature Rise Test

Location	Name	Air Velocities [m/s]	
		Vault 1	Vault 2
1.1	v Air Flow-shield	0.08	0.06
1.2	v Air Flow-shield	0.08	0.17
2.1	v Air Flow-shield	0.41	0.06
2.2	v Air Flow-shield	0.59	0.09
3.1	v Air Flow-shield	0.32	0.09
3.2	v Air Flow-shield	0.29	0.1
4.1	v Air Inlet	0.25	0.88
4.2	v Air Inlet	0.29	0.98
5.1	v Air Inlet	0.3	0.94
5.2	v Air Inlet	0.34	0.9
6.1	v Air Inlet	0.31	0.89
6.2	v Air Inlet	0.31	0.89
7.1	v Air Outlet	0.19	0.58
7.2	v Air Outlet	0.28	0.64
8.1	v Air Outlet	0.27	0.81
8.2	v Air Outlet	0.31	0.77
9.1	v Air Outlet	0.3	0.91
9.2	v Air Outlet	0.35	0.92

H.2. Vault Construction

The following images give an overview into the construction of the vault that was used for testing.



Figure H.2.: Transformer in Vault



Figure H.3.: Flow guard viewed from above



Figure H.4.: Vault 1: Box-Setup

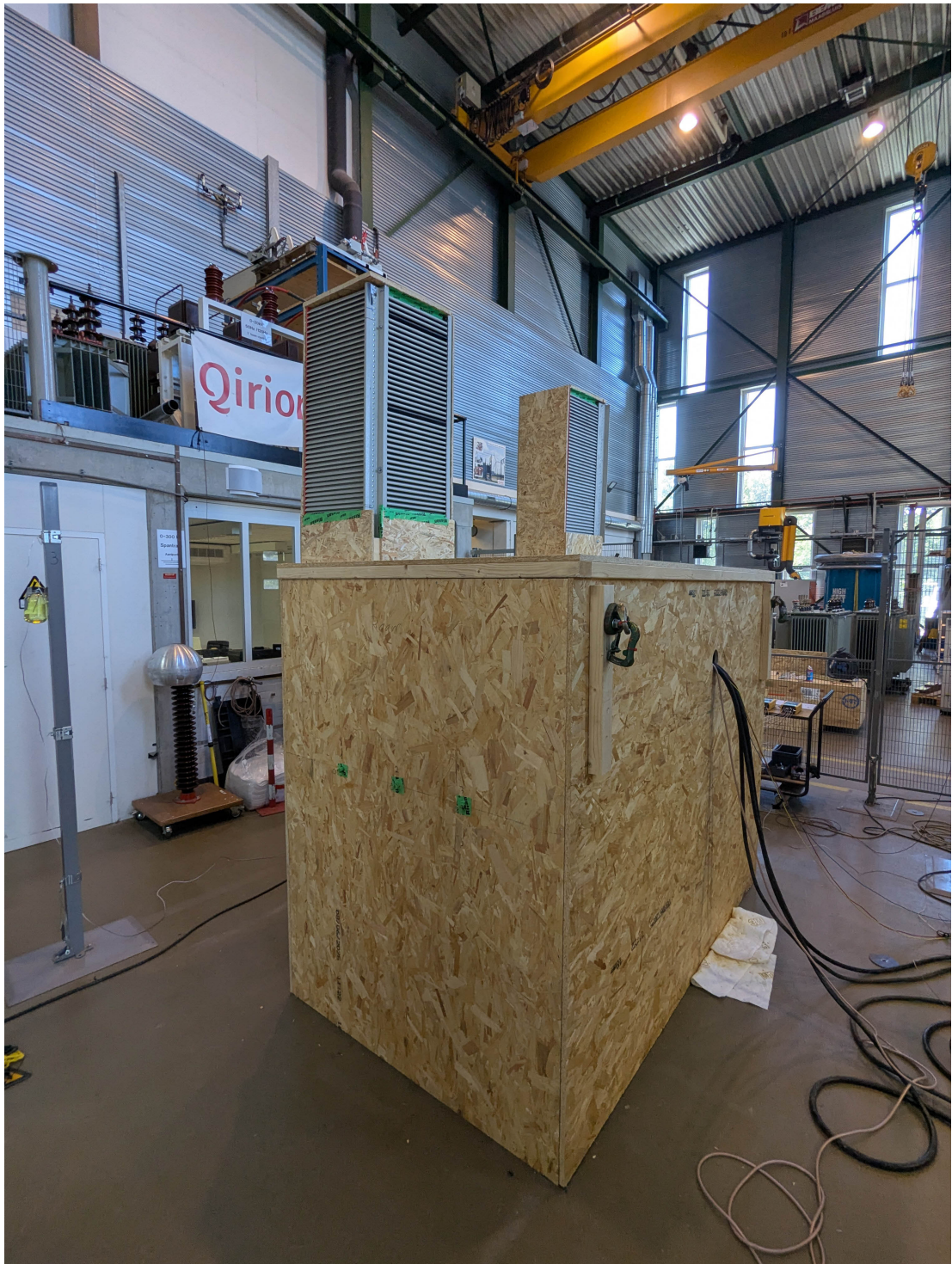


Figure H.5.: Vault 2: Cabinet-Setup

H.3. Sensor Placement

Images of sensor locations. Sensors were taped on by insulated metallized tape. Thermal sensors placed in air were shielded from IR radiation by metallized tape.



Figure H.6.: Full view of the transformer and placed sensors

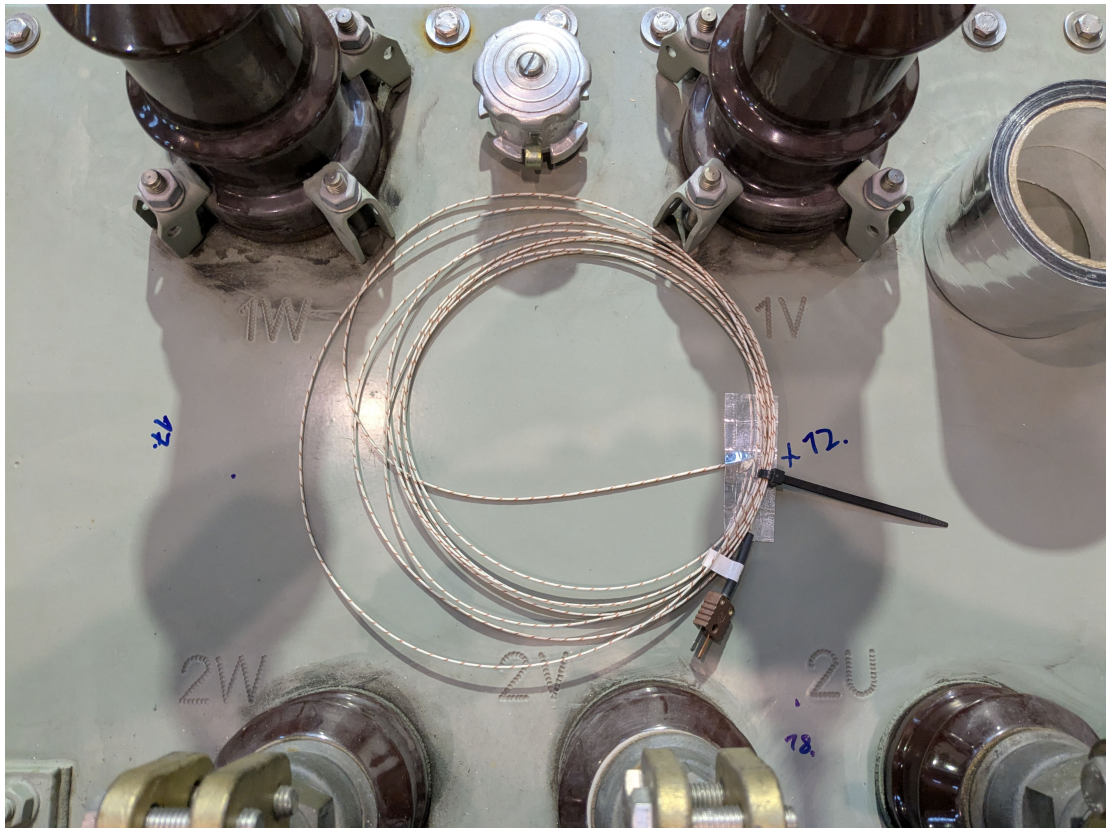


Figure H.7.: Sensor locations on the top lid of the Transformer



Figure H.8.: Sensor locations on the long side fin

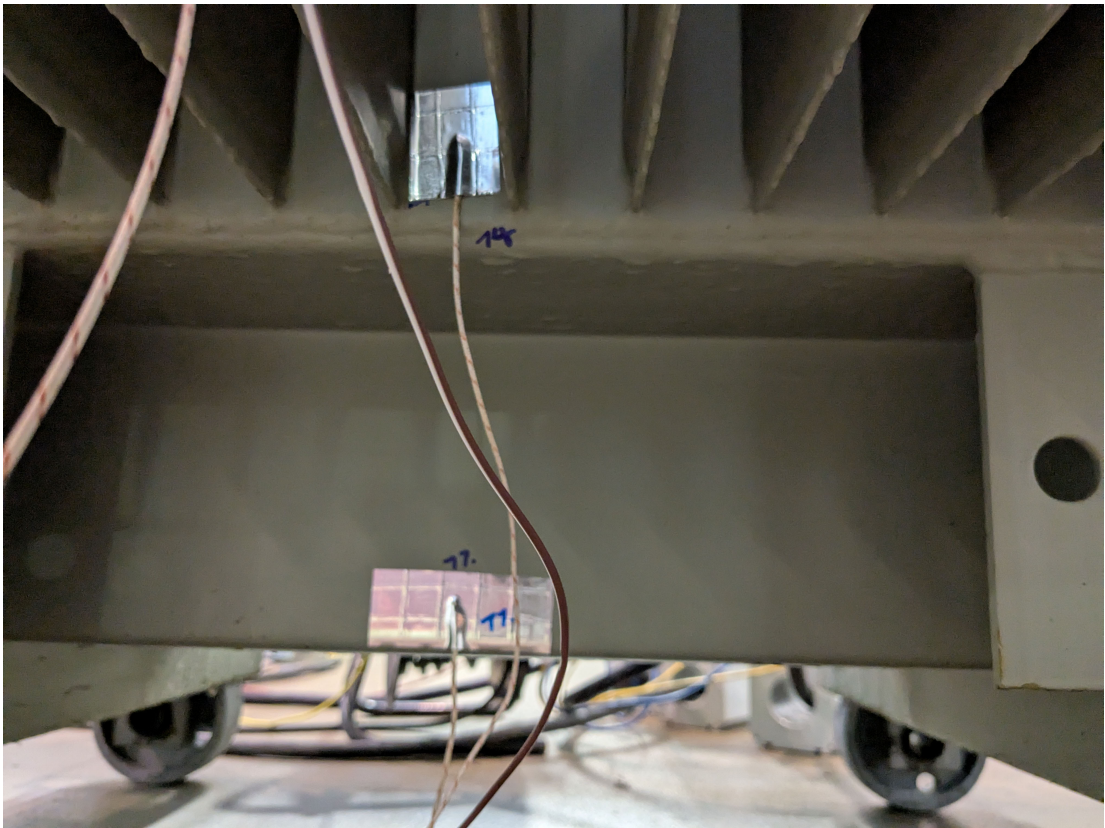


Figure H.9.: Sensor locations on the underside of the long side fin



Figure H.10.: Sensor locations on the short side fin

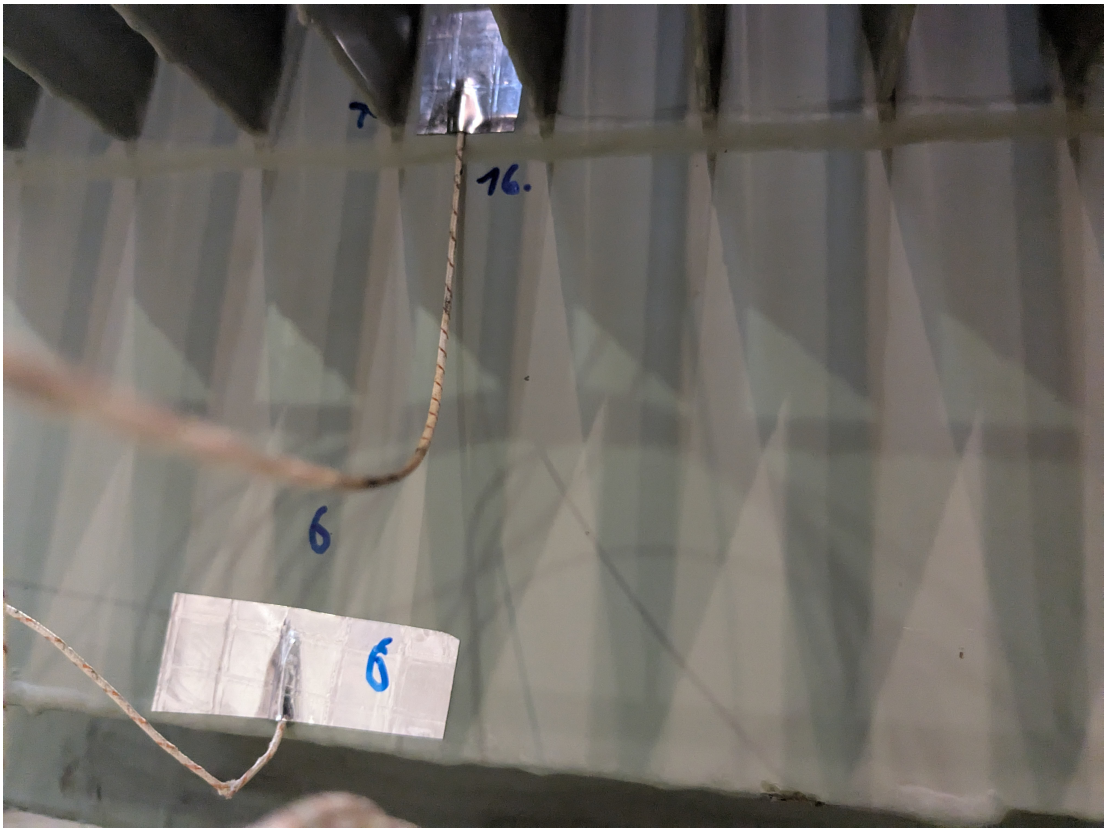


Figure H.11.: Sensor locations on the underside of the short side fin



Figure H.12.: Sensor locations for air temperature inside the vault

Sensors for flow measuring were not present constantly during the experiment. Locations were pre drilled and small tubes were placed in the holes through which flow measurements could be preformed.



Figure H.13.: Sensor locations for measuring flow in the flow shield, for Vault 1 and 2. (1, 2, 3, left to right)



(a) Flow Locations Vault 1 Inlet



(b) Flow Locations Vault 1 Outlet

Figure H.14.: Sensor locations for measuring flow on Vault 1 in- and outlet



(a) Flow Locations Vault 2 Inlet

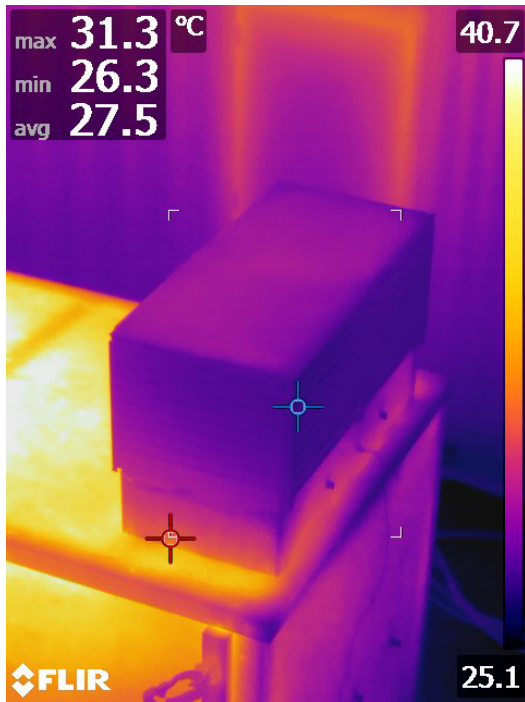


(b) Flow Locations Vault 2 Outlet

Figure H.15.: Sensor locations for measuring flow on Vault 2 in- and outlet

H.4. IR-Thermography

Emissivity was not calibrated. Temperatures should only be interpreted for their distribution, not magnitude.

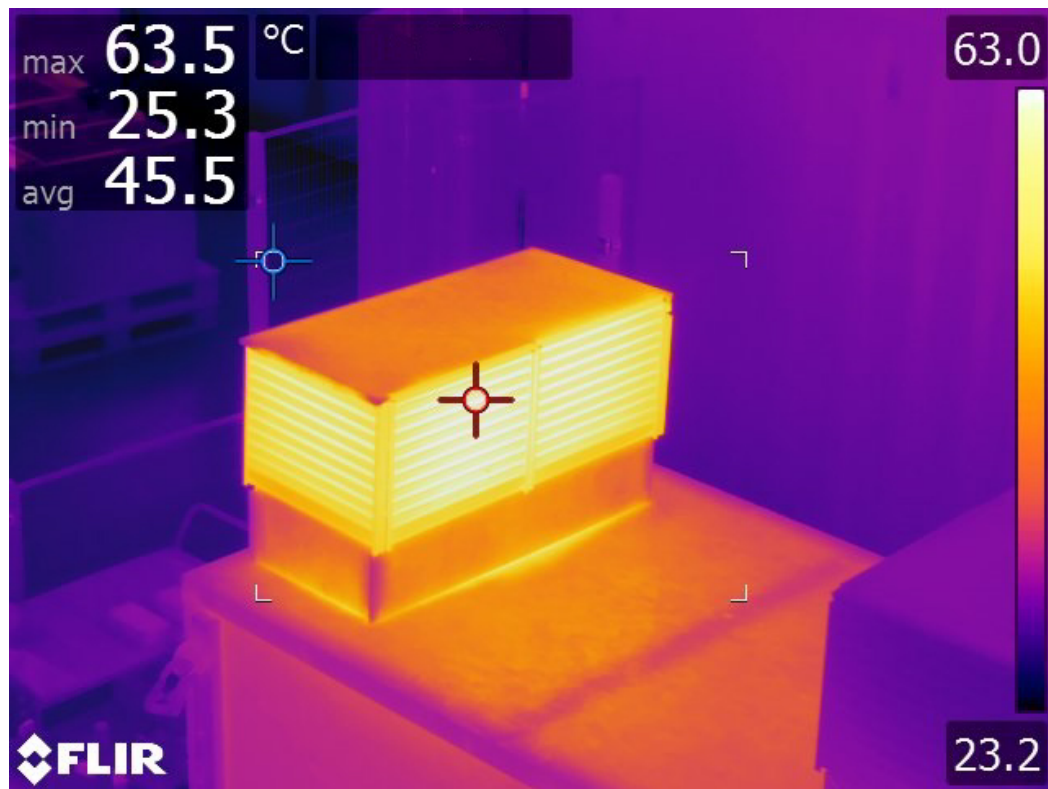


(a) IR image of Inlet



(b) Colour image of inlet

Figure H.16.: IR and colour images of inlet Vault 1

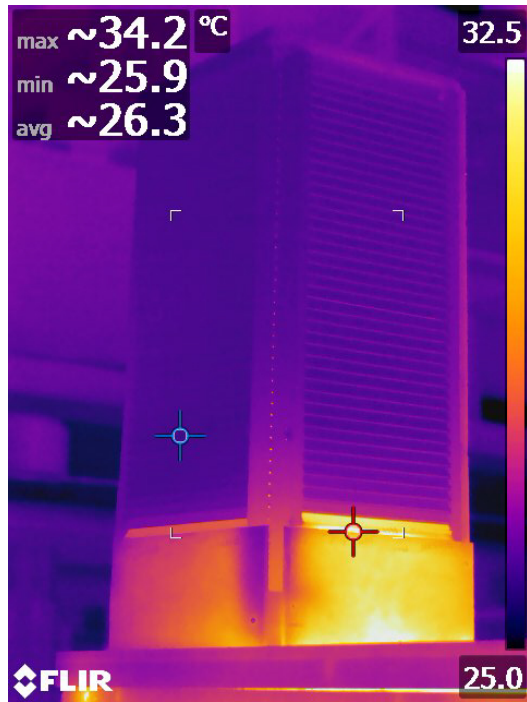


(a) IR image of outlet



(b) Colour image of outlet

Figure H.17.: IR and colour images of outlet Vault 1

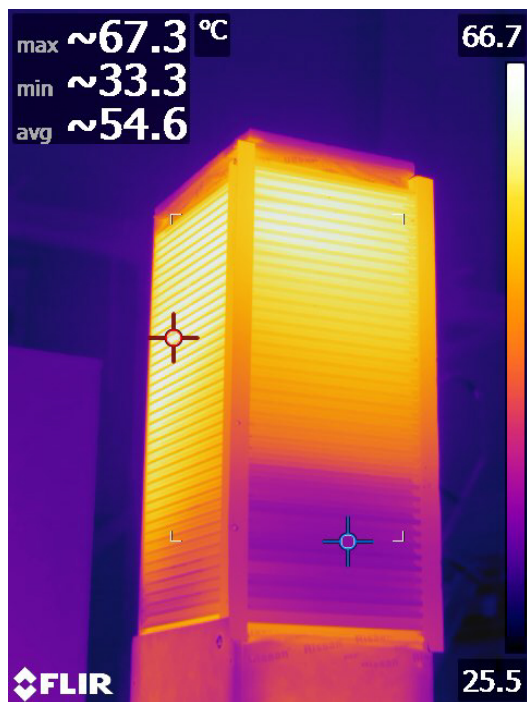


(a) IR image of Inlet



(b) Colour image of inlet

Figure H.18.: IR and colour images of inlet Vault 2



(a) IR image of Inlet



(b) Colour image of inlet

Figure H.19.: IR and colour images of inlet Vault 2

I. Plots for Chapter 6

I.1. Free Standing

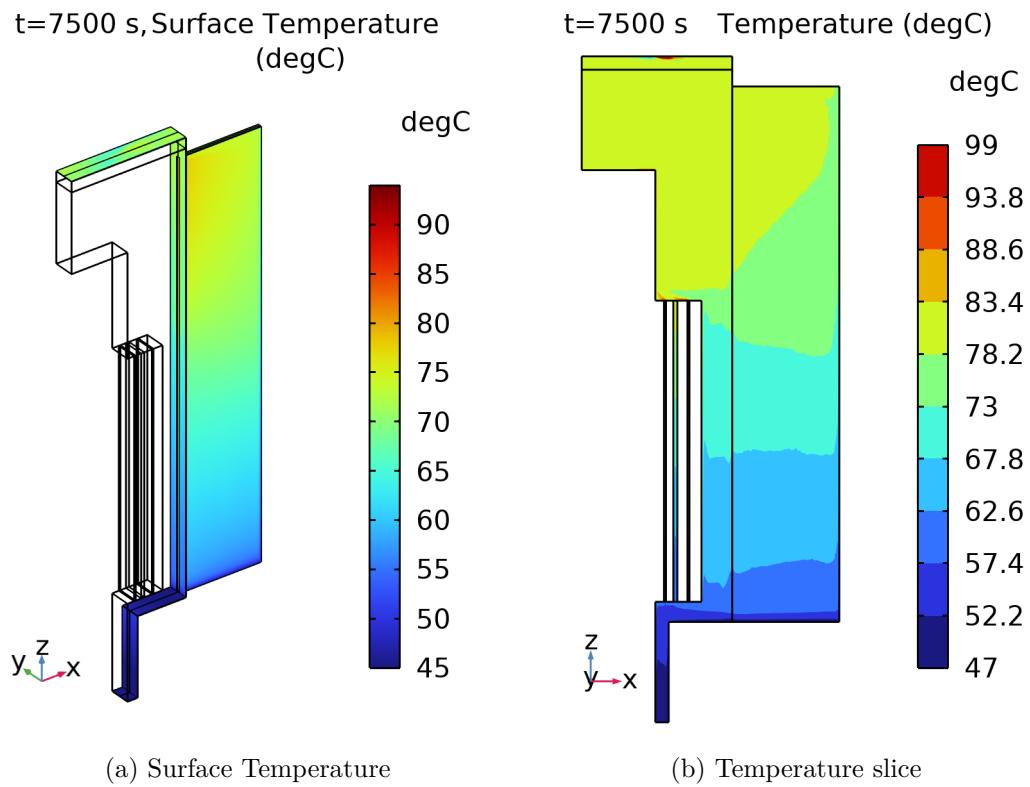


Figure I.1.: Temperatures on the outside, and inside of the *fin-slice* model. Validated free-standing transformer from Section 6.2.

I.2. Box-Setup

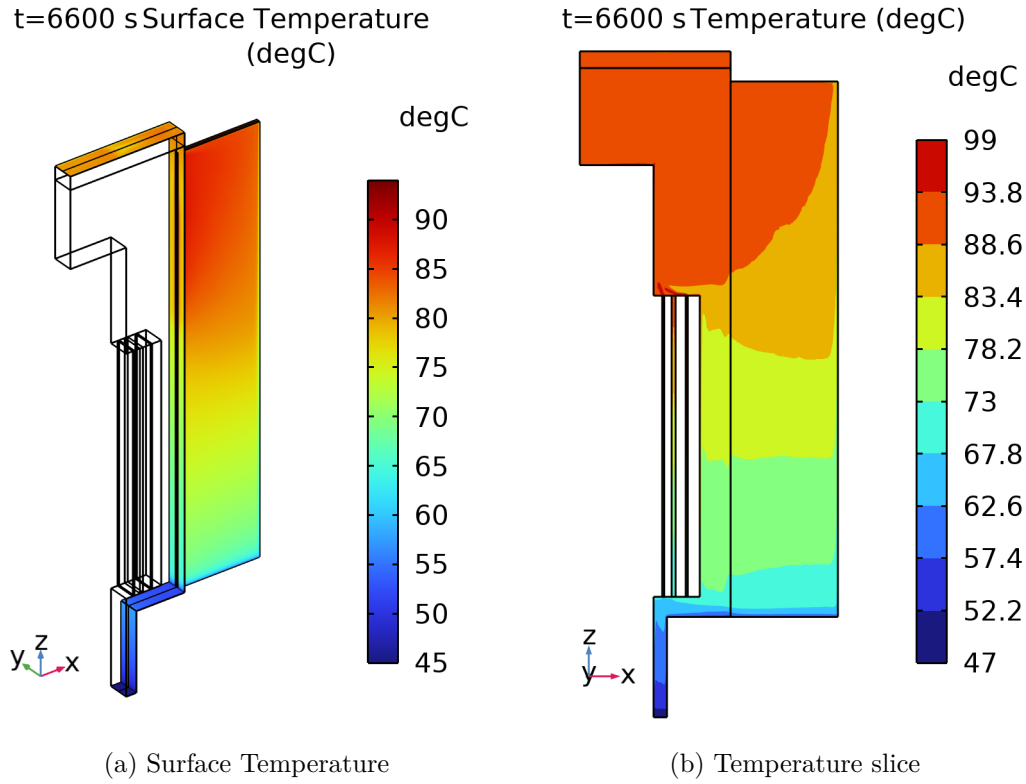


Figure I.2.: Temperatures on the outside, and inside of the *fin-slice* model. Validated box-setup from Section 6.3.

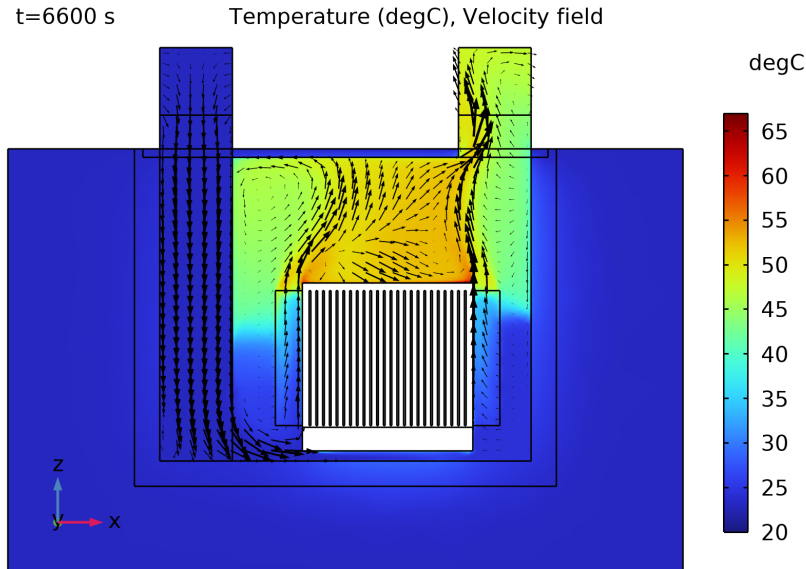
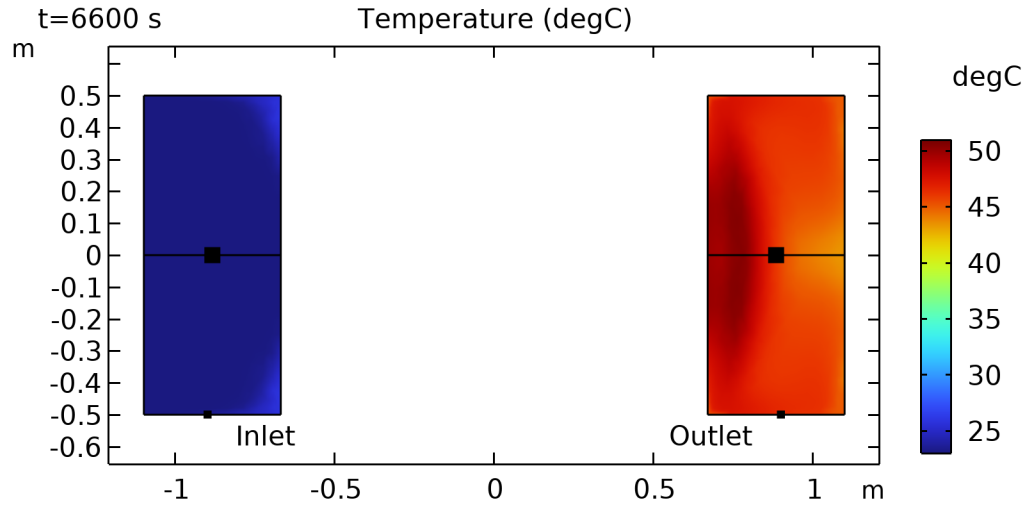
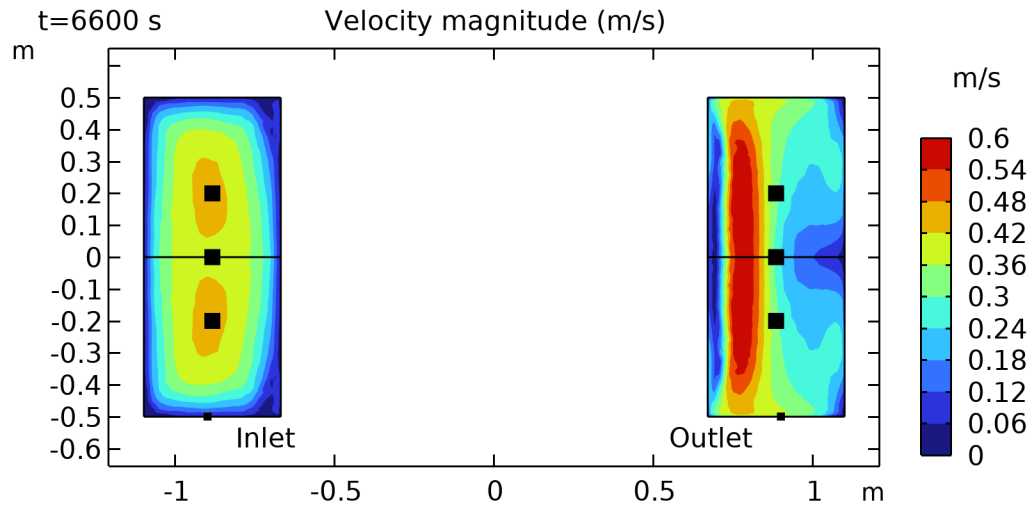


Figure I.3.: Cross sectional temperature and flow field in the vault. Arrows scaled by velocity magnitude. Validated box-setup from Section 6.3.



(a) In-/outlet temperature



(b) In-/outlet velocity

Figure I.4.: In-/outlet temperatures and velocities, black dots indicate sensor locations.
Validated box-setup from Section 6.3.

I.3. Cabinet-Setup

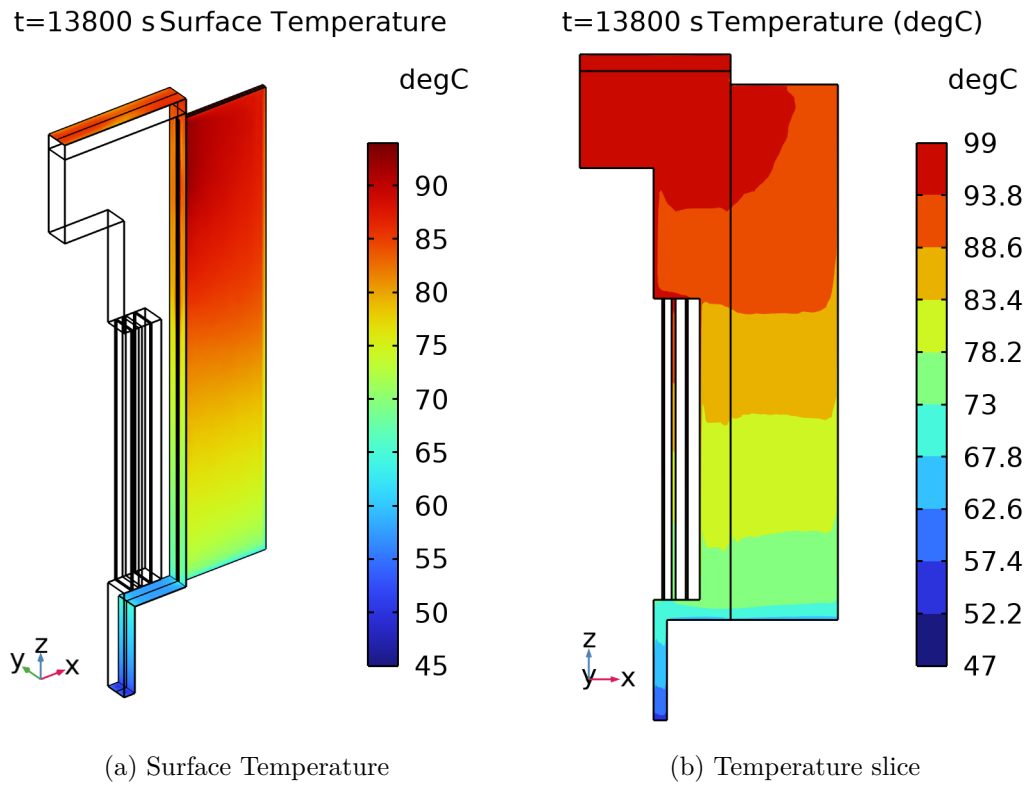
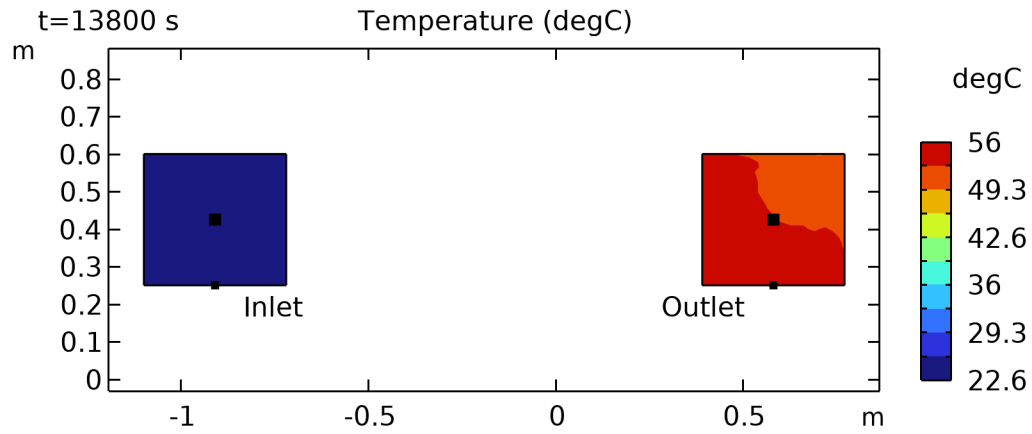
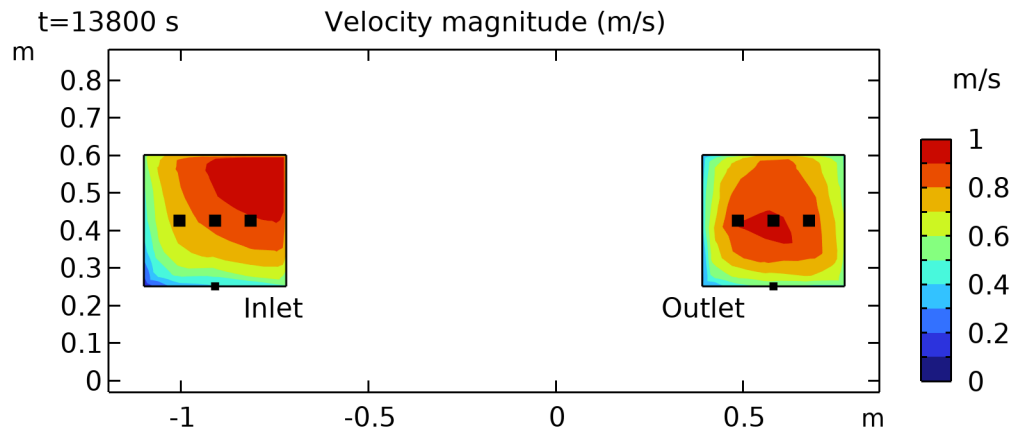


Figure I.5.: Temperatures on the outside, and inside of the *fin-slice* model. Validated cabinet-setup from Section 6.4.



(a) In-/outlet temperature



(b) In-/outlet velocity

Figure I.6.: In-/outlet temperatures and velocities, black dots indicate sensor locations. Validated cabinet-setup from Section 6.4.

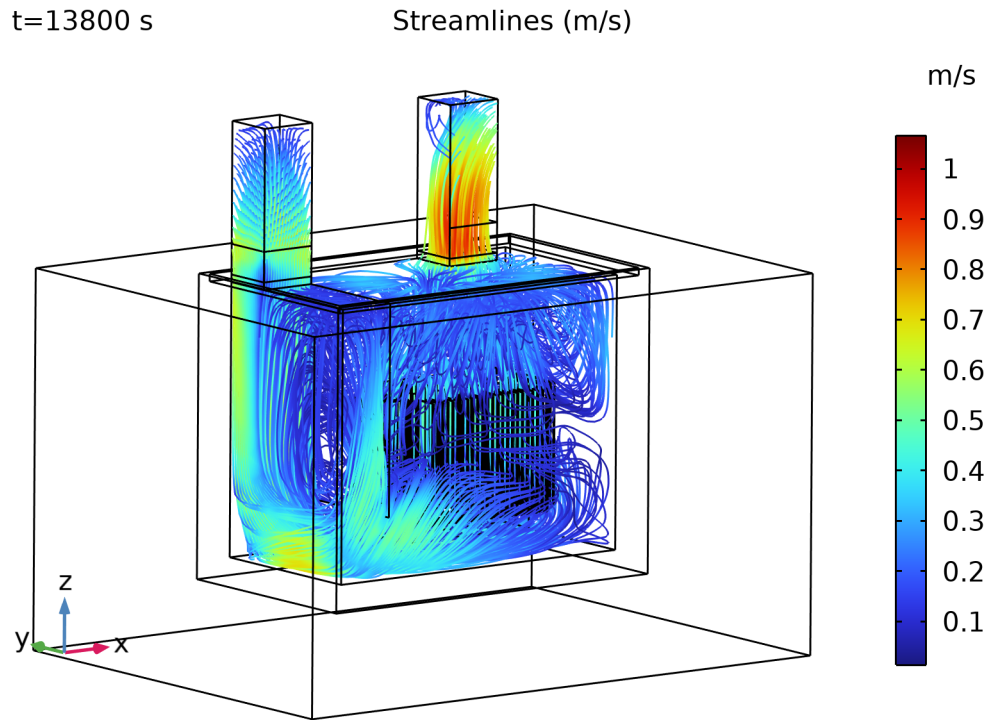


Figure I.7.: Streamlines in the cabinet-setup. Colour indicates flow velocity magnitude in m/s. Recirculation of air in intake region, as well as above transformer visible. Validated cabinet-setup from Section 6.4.

I.4. Model Variation

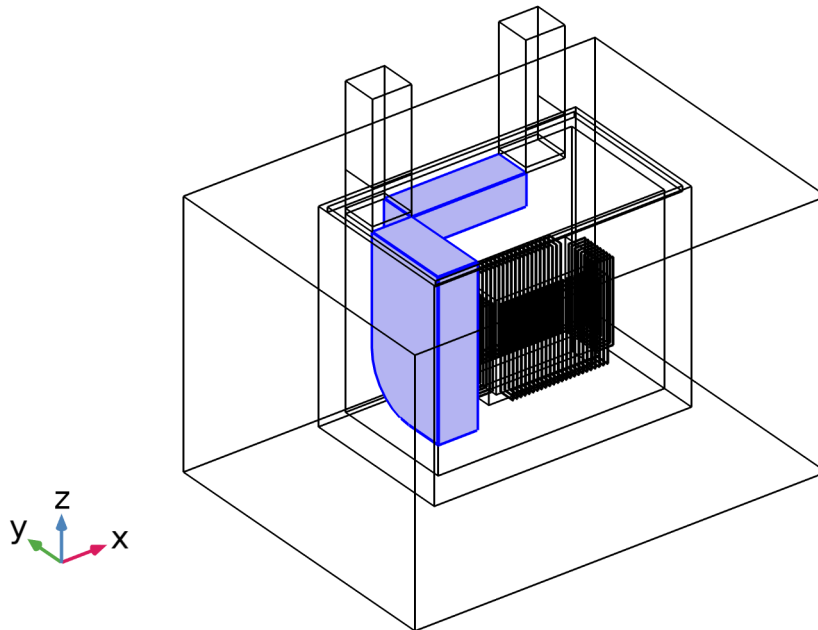


Figure I.8.: Introduced flow restrictions in the cabinet-setup, highlighted in blue. Curved block on left is for preventing recirculation in the down draft, while the cuboid on the top right is for the restrictions faced by the incoming cables. Section 6.5.

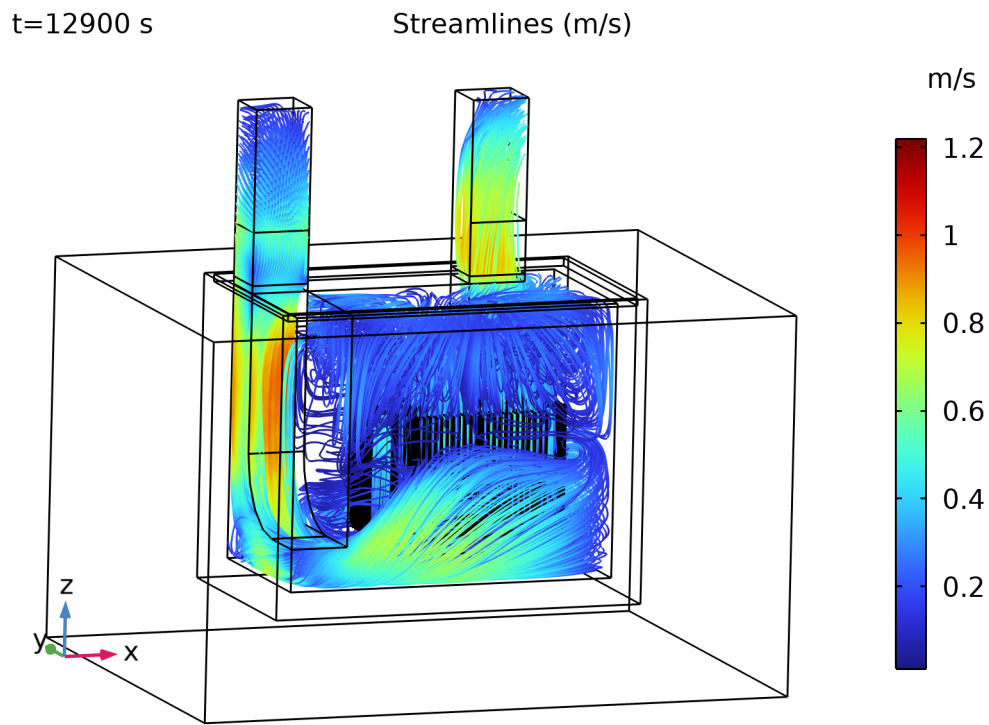


Figure I.9.: Streamlines in the cabinet-setup with flow guards. Colour indicates flow velocity magnitude in m/s. Recirculation of air in intake region now interrupted by a solid block, enabling a more efficient intake of air, and resulting in higher flow velocities. Cabinet-setup with added flow guard from Section 6.5.

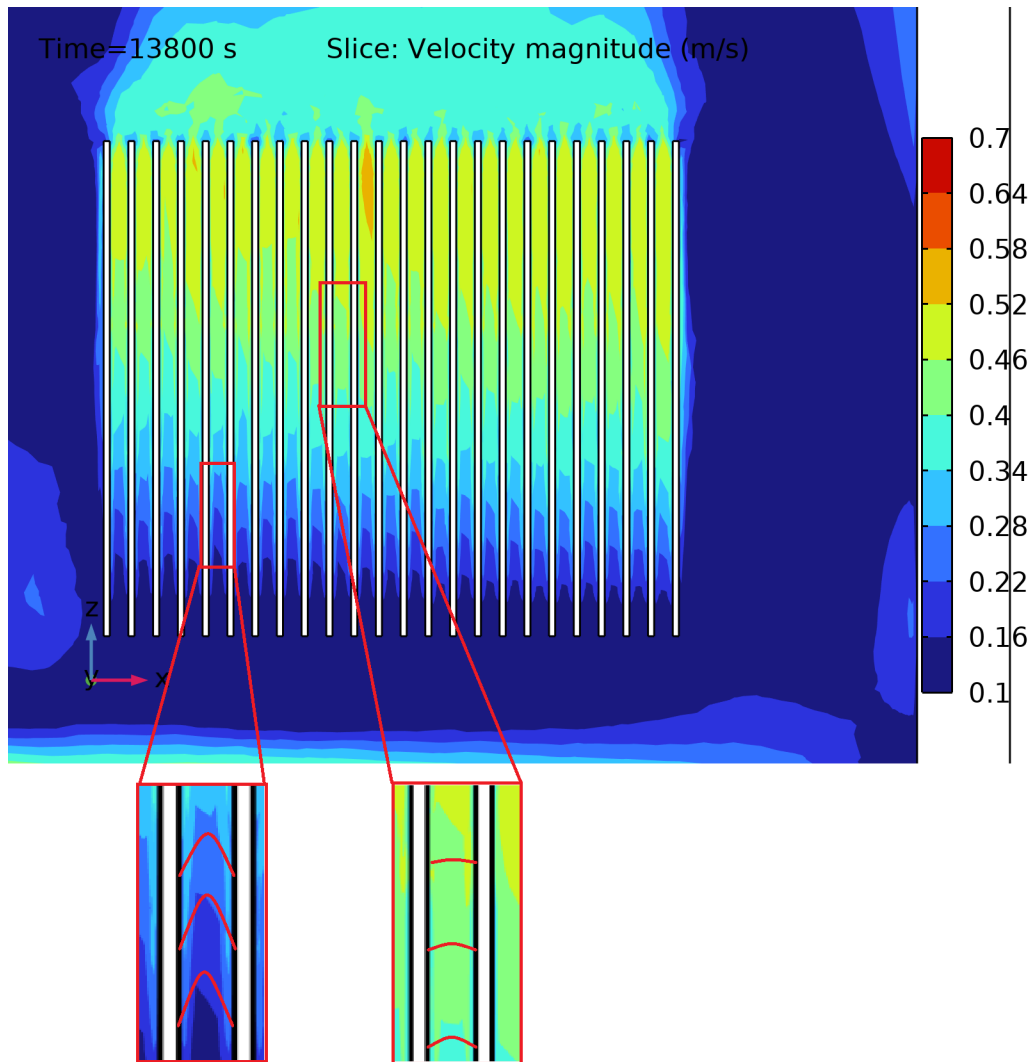


Figure I.10.: Flow velocities through the transformer fins, from Section 6.6. Regions on the undersides of the fins, in which flow speeds are not fully developed, show a different cross sectional profile than those in the mid-upper parts of the fins.