# HoST Calculus – Advanced Software for Transformer Thermal Analysis

Implementation of Detailed Static and Dynamic Thermal-Hydraulic Network Model (THNM)

# Introduction

- During power transformer operation, load variations cause changes in energy losses and heating power.
- The temperature of the external cooling fluid also fluctuates, leading to variations in internal transformer temperatures.
- These thermal changes can be managed by adjusting the cooling system, such as modifying the number of active fans.
- To prevent transformer failure and accelerated insulation aging, the temperature must remain within critical limits and rated values.
- A transformer's thermal characteristics are evaluated through a standard heat run test under steady-state conditions (IEC 60076-2).

# Overview

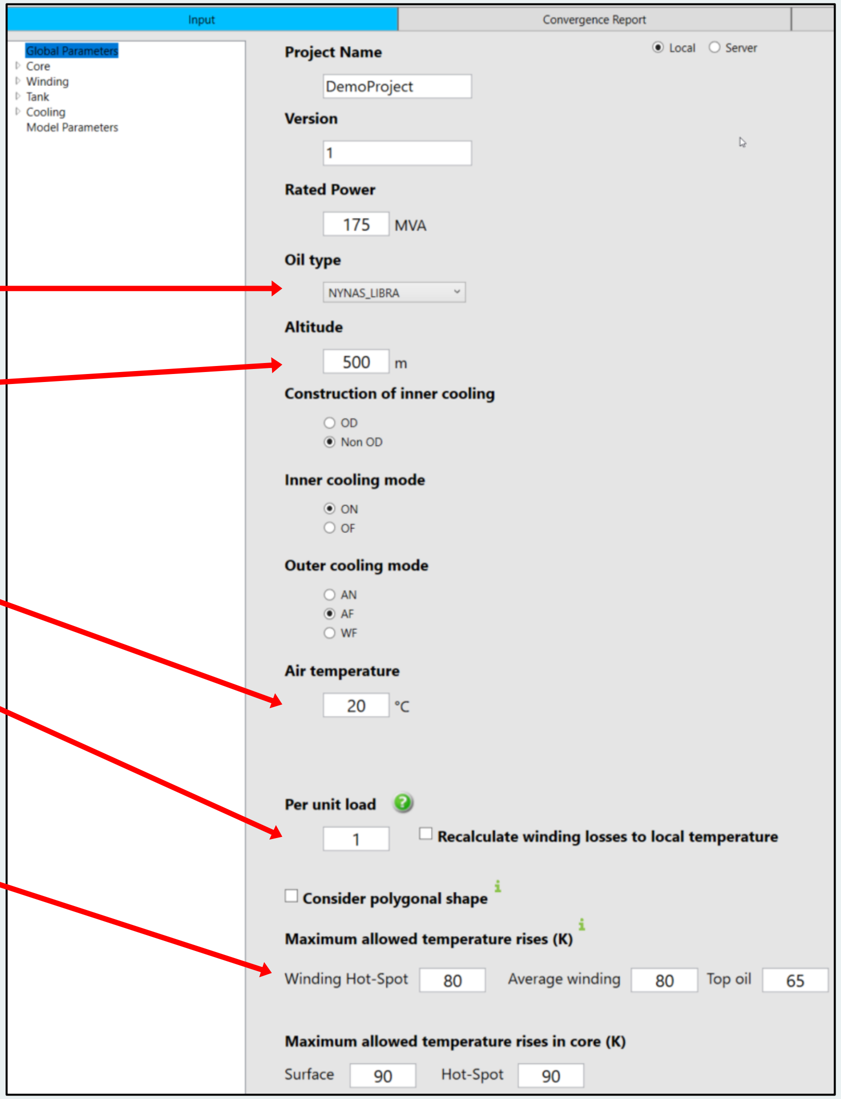
- Static HoST Calculus is software designed  tool for thermal analysis of liquid-immersed oil power transformers (PT).
- Dynamic HoST Calculus is a software for thermal monitoring and estimation of overload possibility.
- Key Benefits:
  - Accurate temperature predictions and hotspot identification.
  - Fast execution (Static HoST: max. 10–15 minutes for complex designs, Dynamic HoST: executable in real time for grid operating conditions).

# Static HoST

- Thermal Design:
  - Predicts temperatures during a standard heat run test (IEC 60076-2).
  - Estimates the hotspot location and temperature rise.
- Safety Margins:
  - Recommended 5 K margin for hotspot, 3 K for top oil.
- Performance:
  - Based on analysis of 146 heat run tests [1], estimated 8.2% increase in profit.
- Input Requirements:
  - Detailed transformer construction data and material properties.
  - No calibration required.

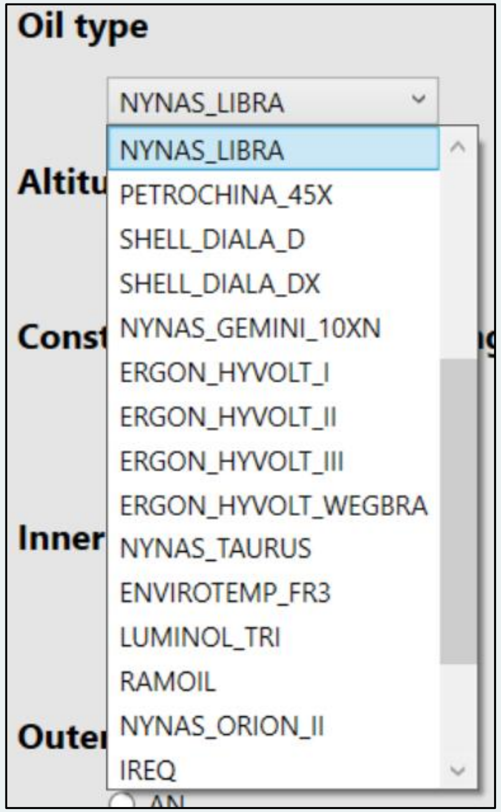
# Input GUI – Global Parameters

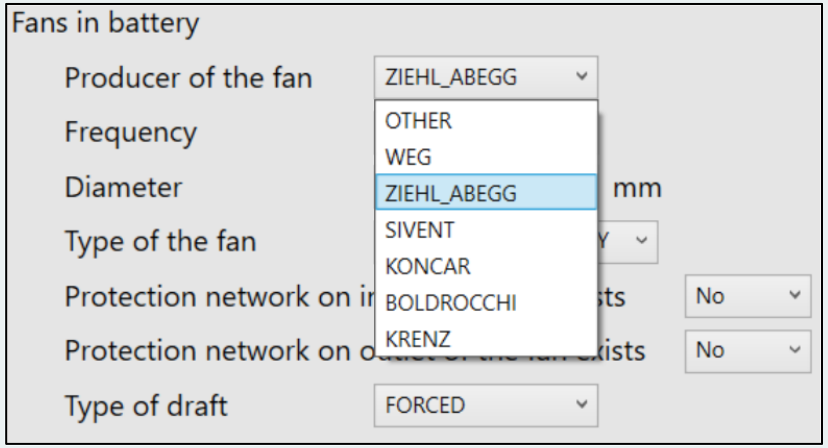
- Thermal Influences:
  - Oil flow and viscosity (dependent on oil type and temperature).
  - Altitude.
  - Ambient air temperature.
  - Losses at specified per unit load.
- Guaranteed values



# Database Integration

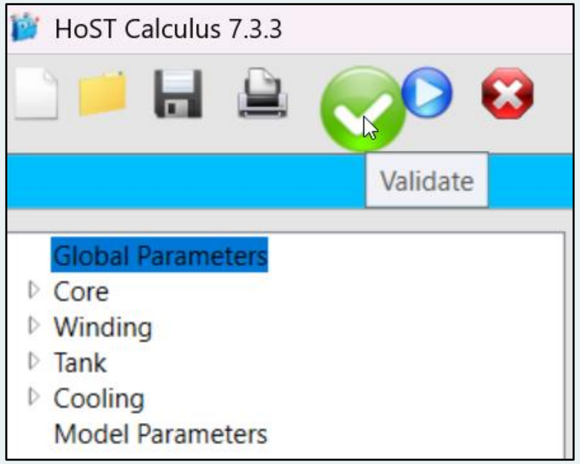
- Built-in databases with characteristics for various types from different manufacturers for:
  - Oil
  - Fans
  - Pumps
  - Radiators
  - Compact coolers

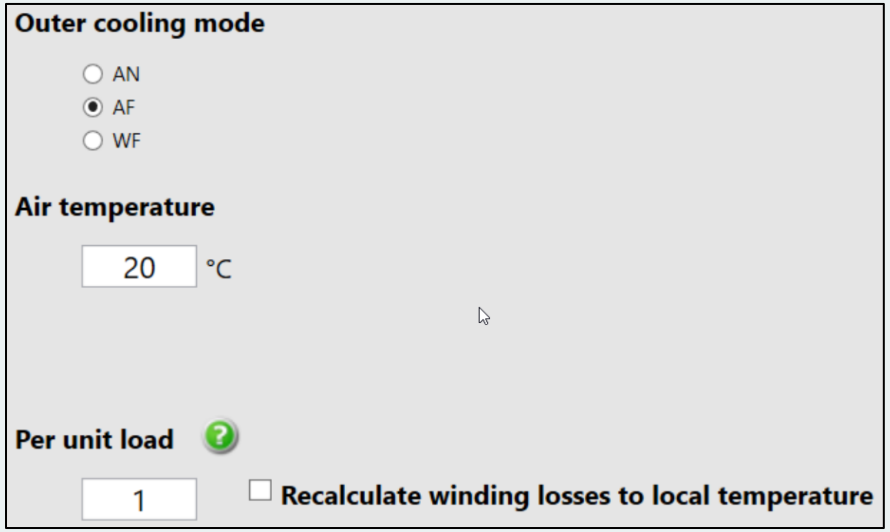


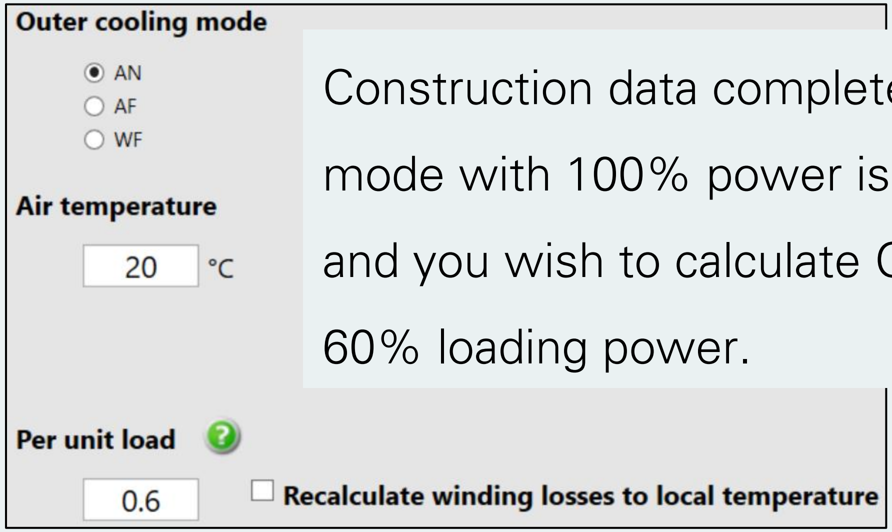



# Integrated Data Entry & Validation

- Efficient Data Entry:
  - Integrated, smart interface for rapid input of transformer design data.
- Validation:
  - Automated warnings for missing or out-of-range data ensure correct input.



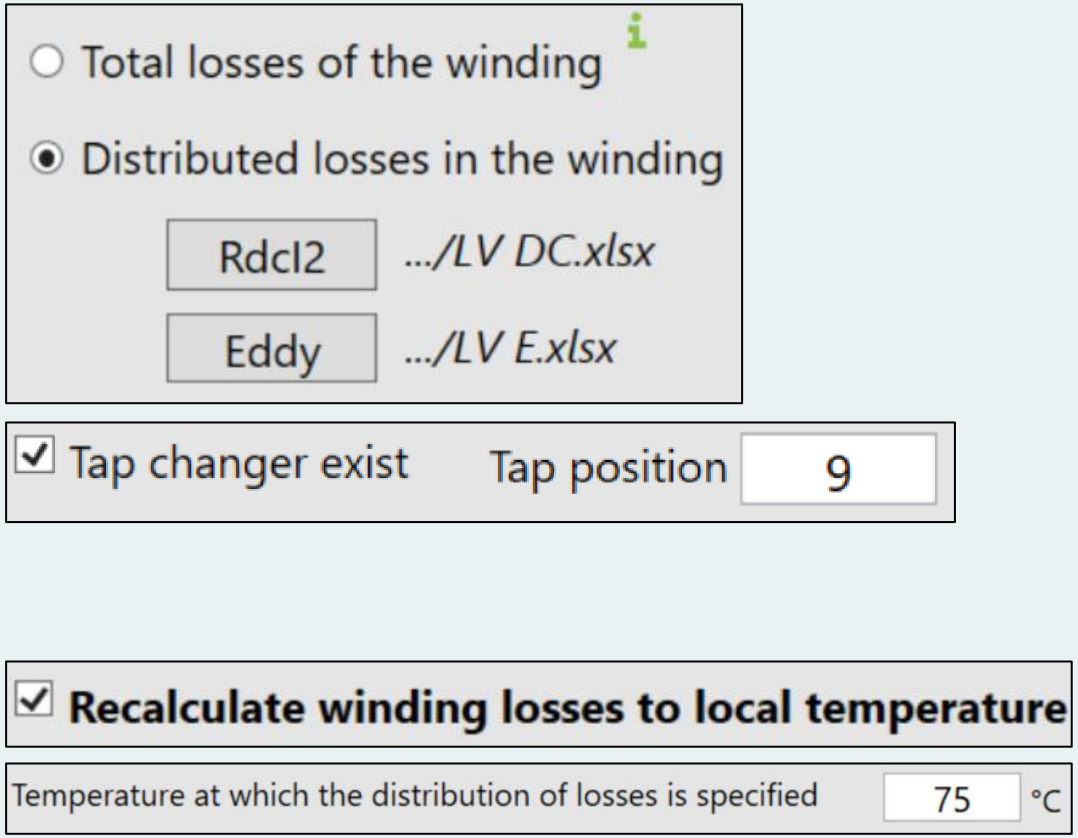




Construction data completed, ONAF mode with 100% power is calculated and you wish to calculate ONAN with 60% loading power.

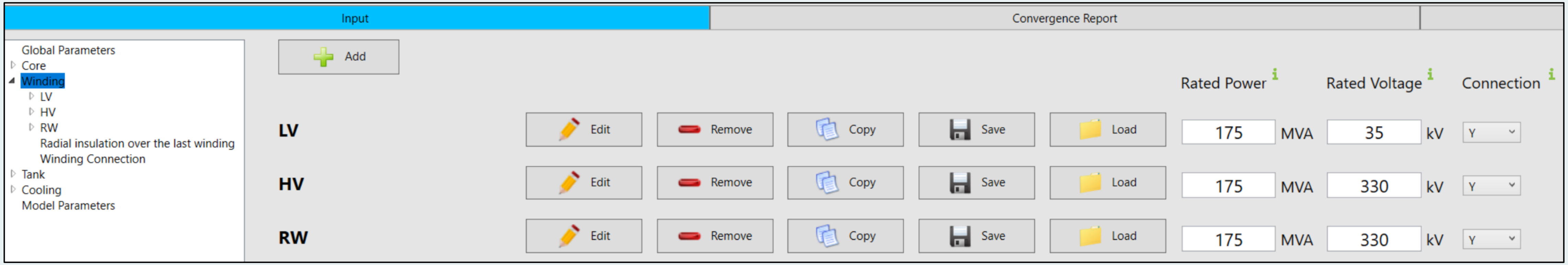
# Winding - Losses

- Import distributed losses from Excel or specify total losses.
- Distributed losses can be loaded for all tap positions, and for calculations the losses corresponding to specified tap are used.
- The losses can be recalculated to local conductor temperatures.

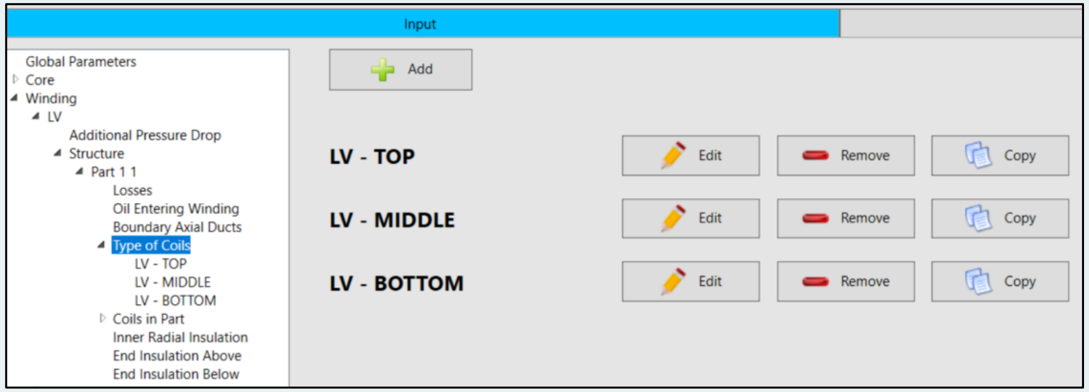


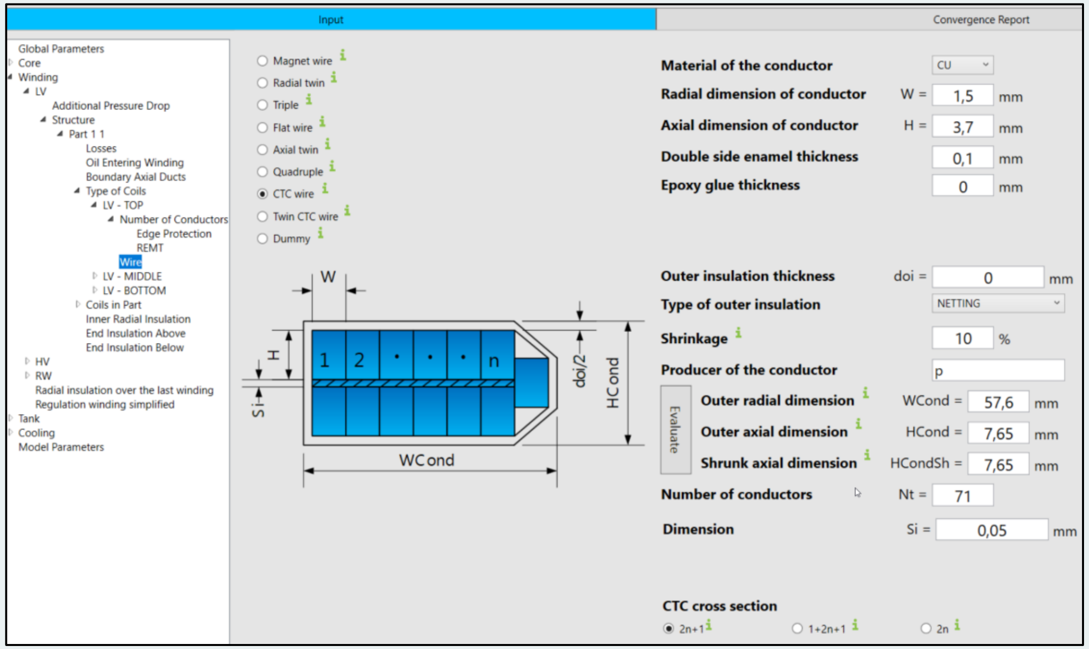
# Winding - Handling

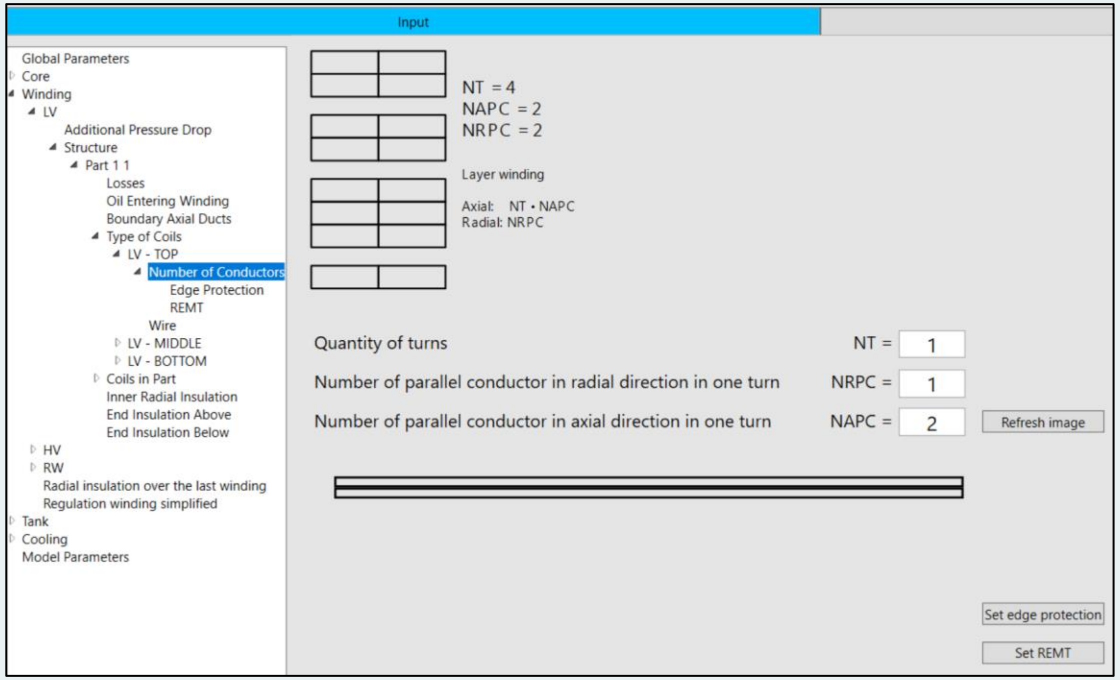
Option to handle complete windings to speed up repetitive design entries.



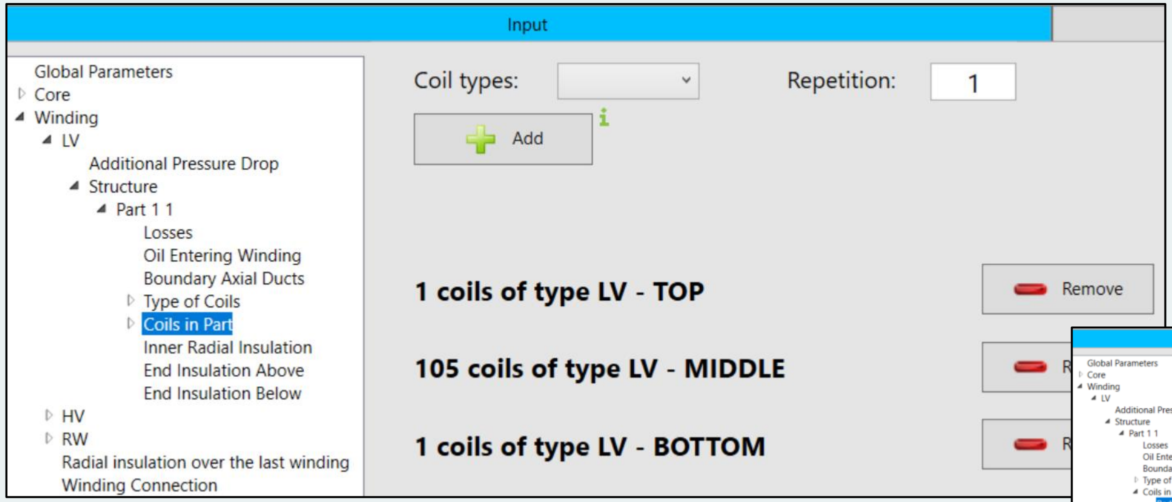
# Winding – Defining coils

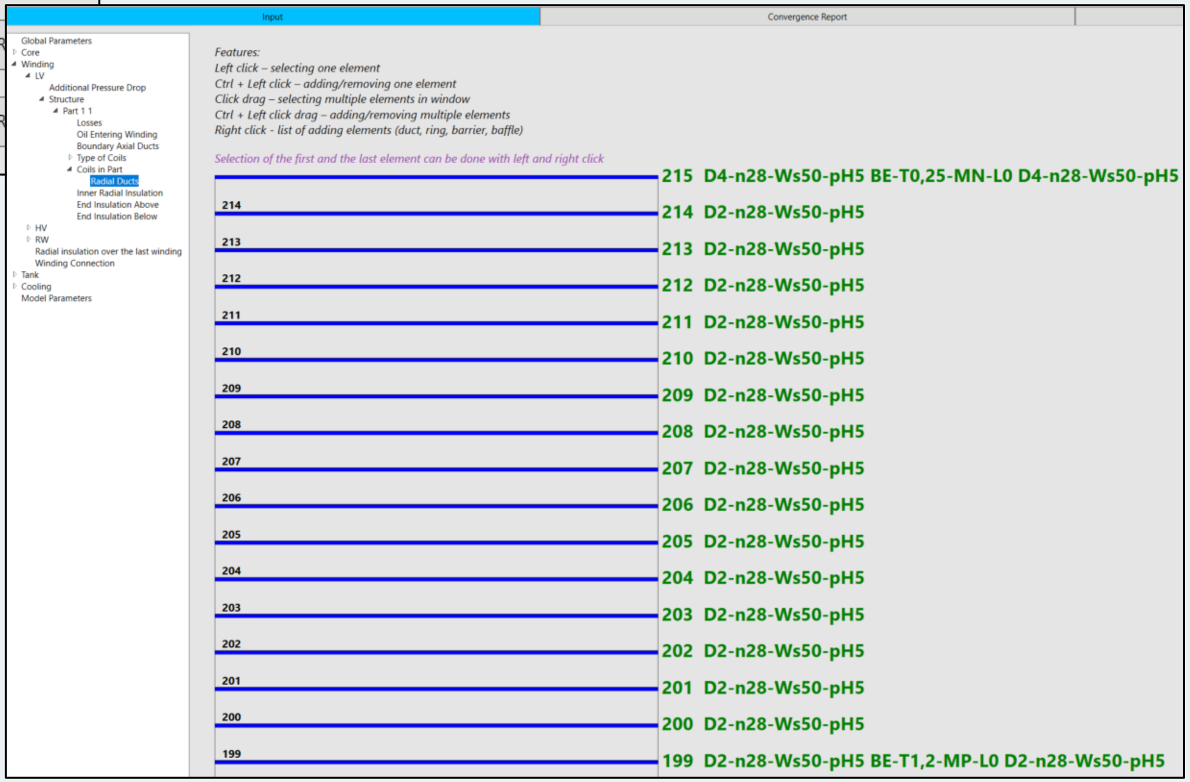


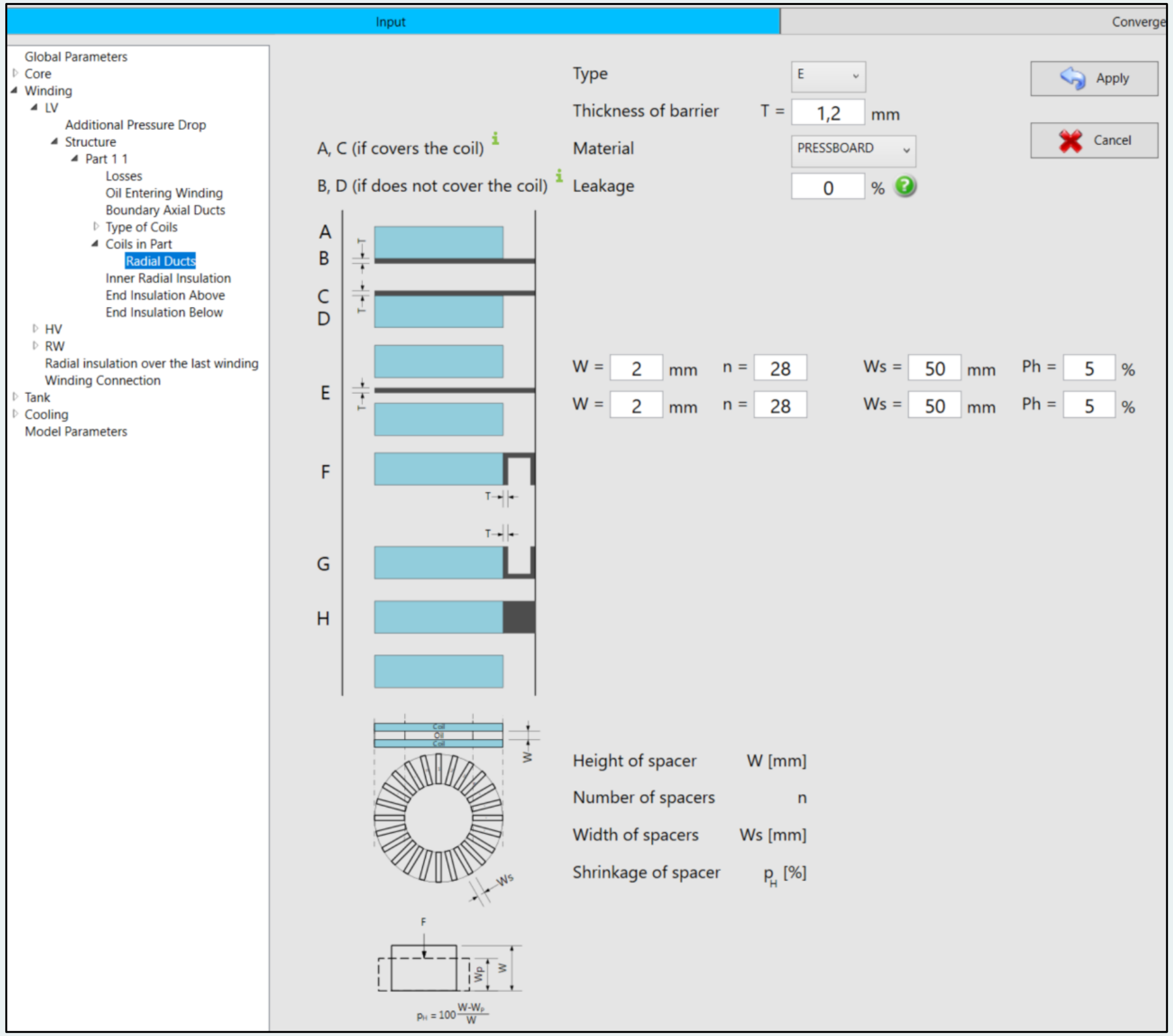
# Coils & Radial ducts in winding part



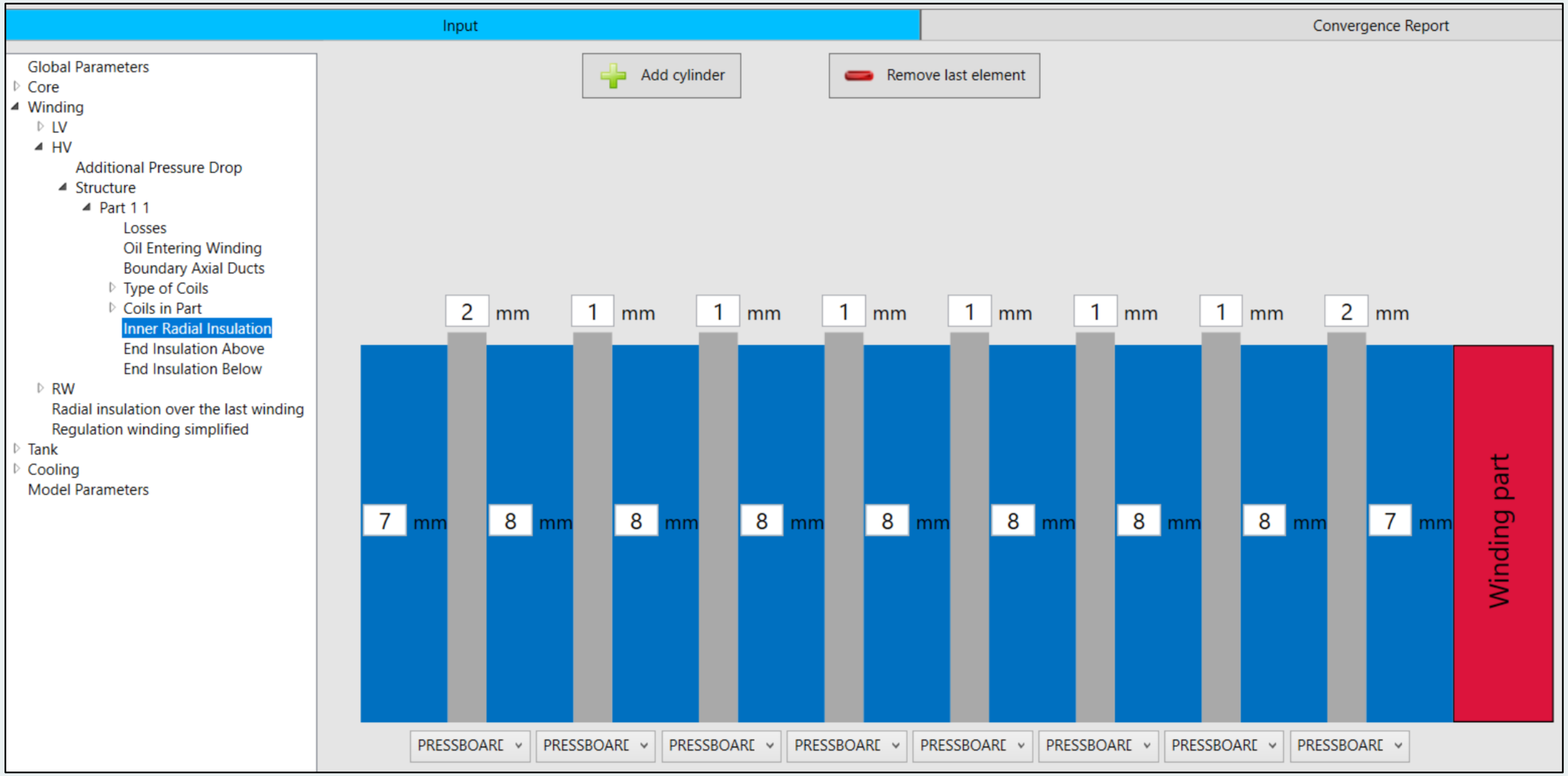




A sample case with 107 coils (each with two axial parallel conductors) results in 107×2 radial ducts plus one extra top duct (totaling 215 ducts).

# Winding – Inclusion of barriers for zig-zag oil flow between conductors



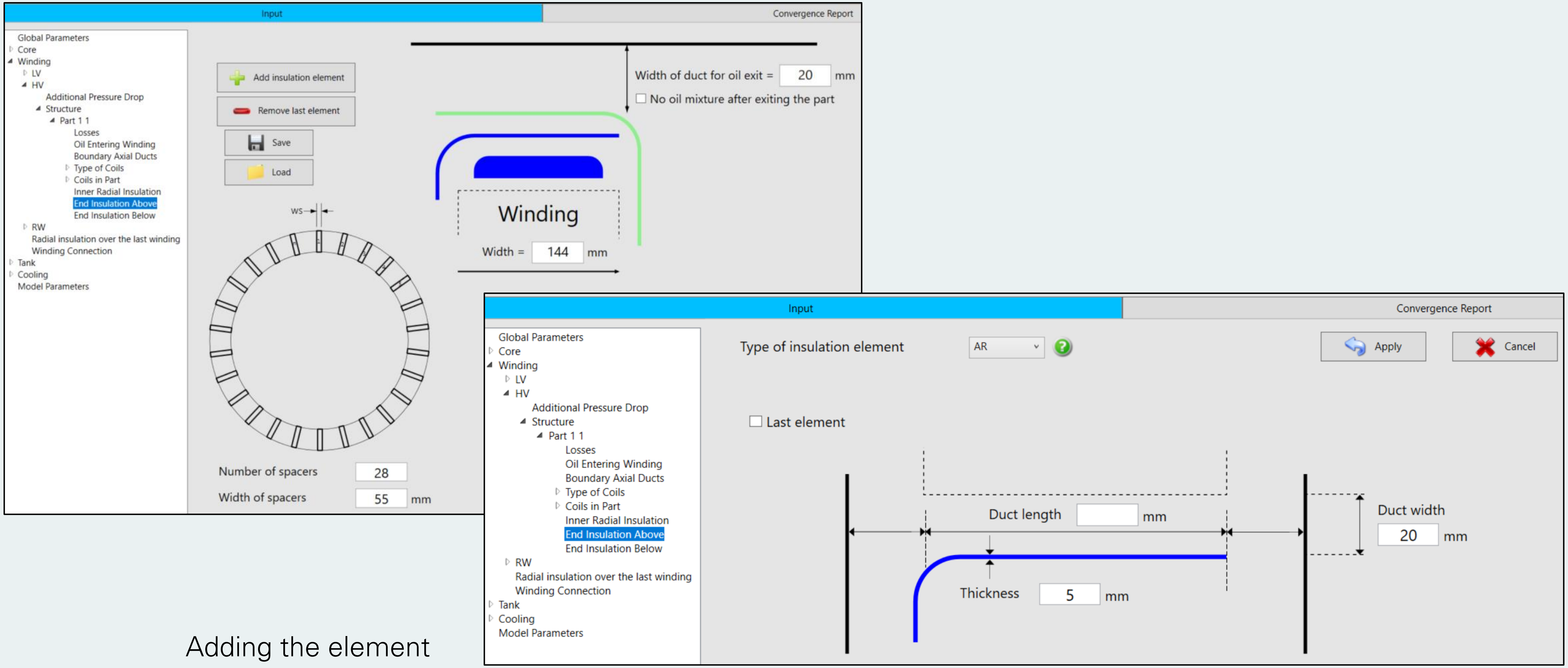
# The insulation between the low-voltage and the high-voltage windings





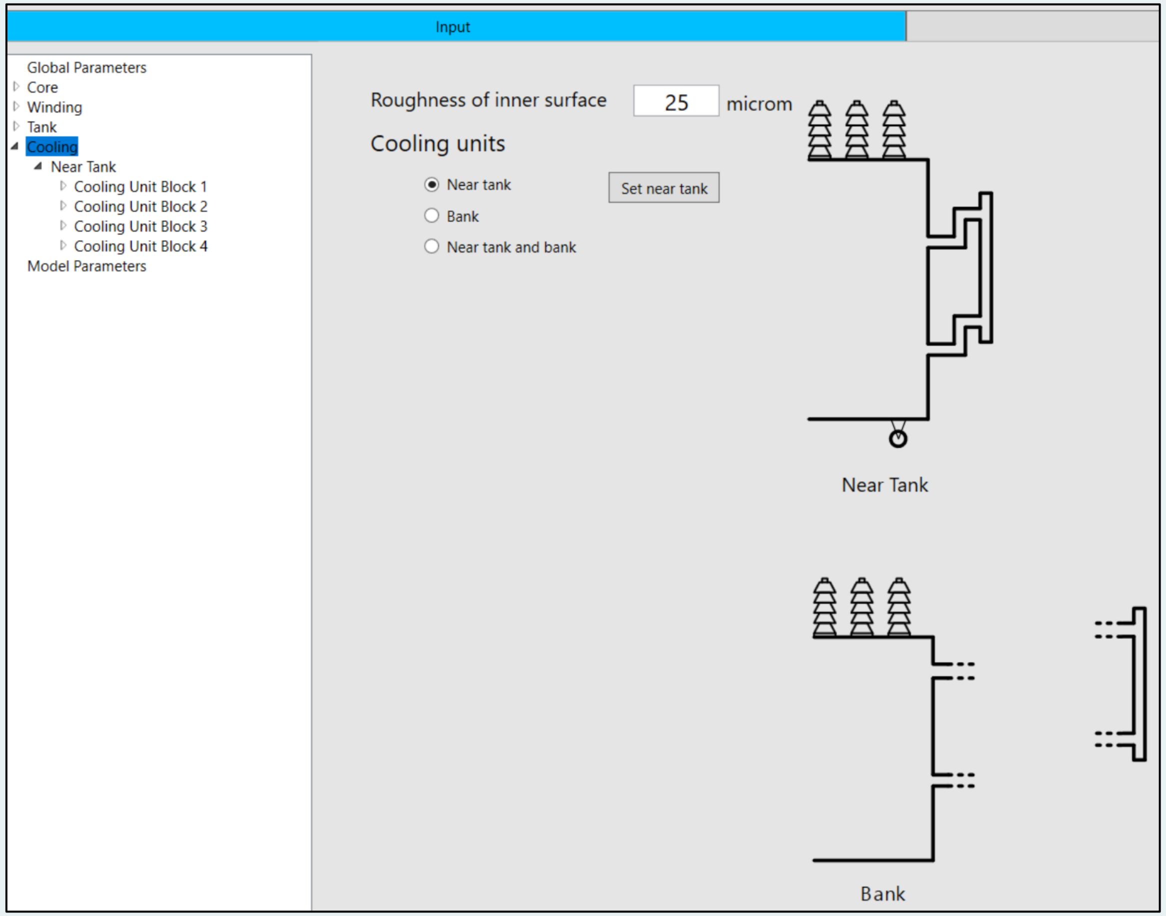

Note: 7 mm cooling ducts are placed on both the inner side of the HV winding and the outer side of the LV winding.

# The insulation between top of HV winding and yoke of the core




Adding the element

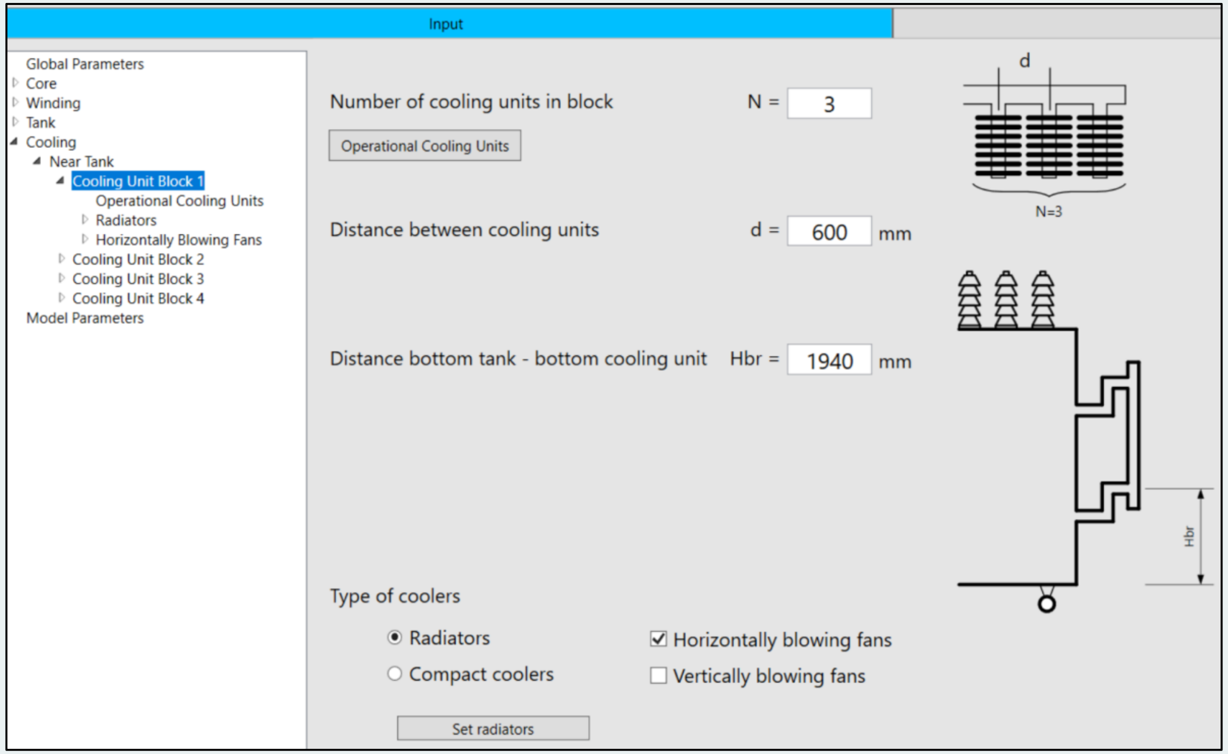
# Outer cooling tab




Options:

- Near tank
- Bank – a piping system connects the bank of cooling units with the tank

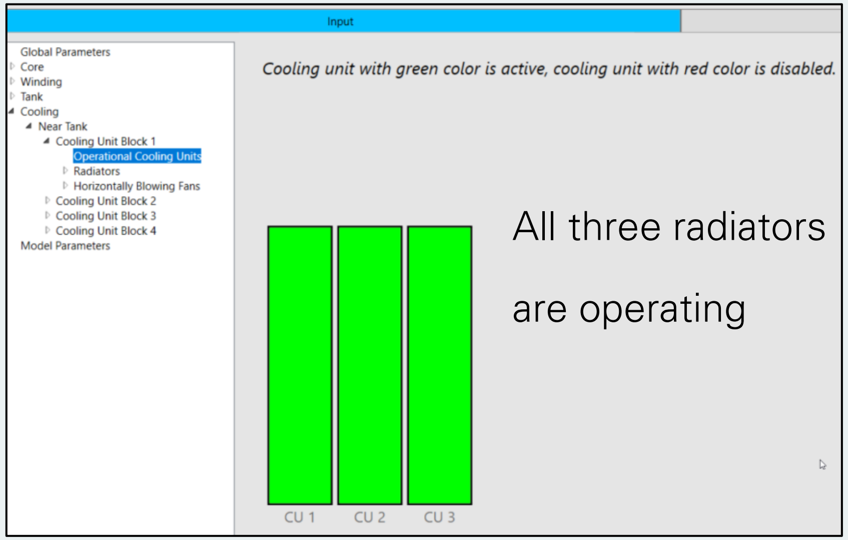
# Cooling unit block

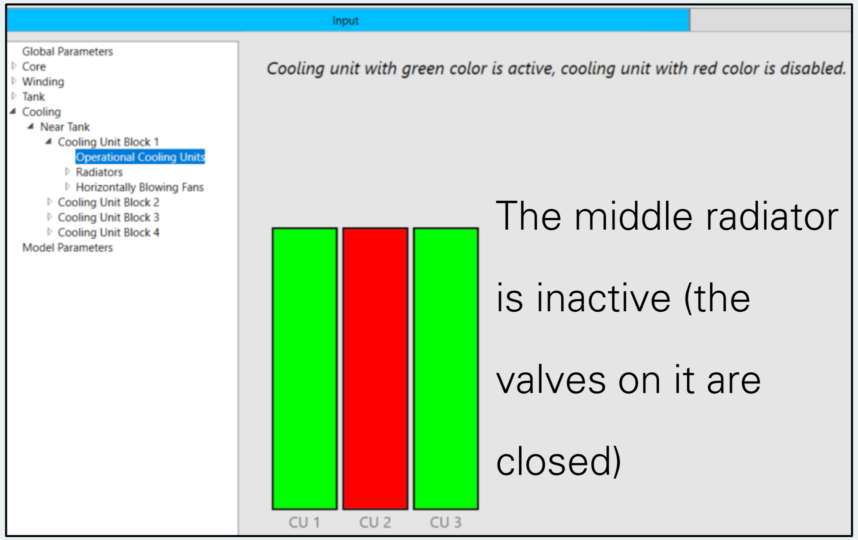


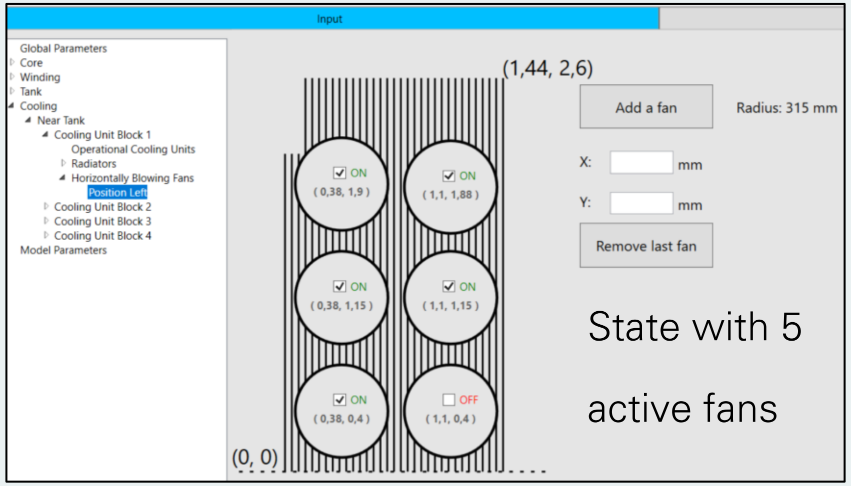

Cooling Unit Composition:

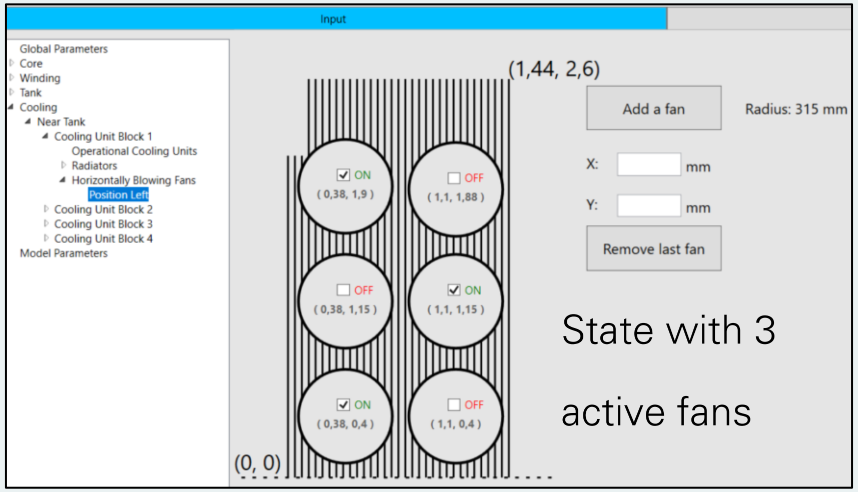
- Consists of radiators or compact coolers.
- In the case of radiators, a cooling unit block is formed as the group of radiators cooled by the group of fans.

# Operating cooling units / operating fans

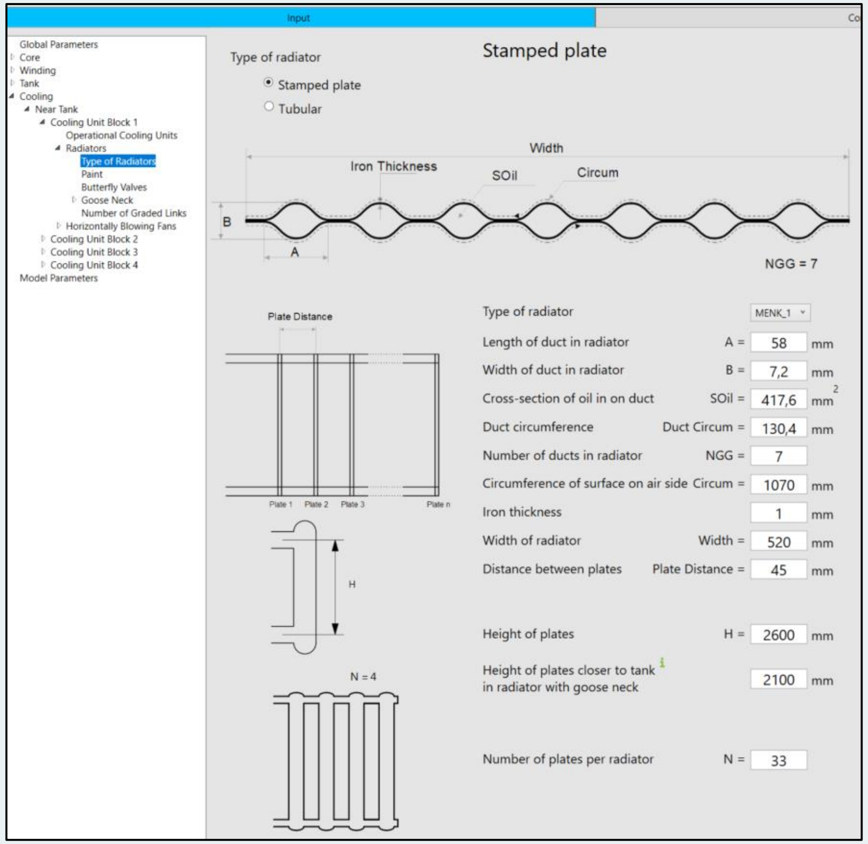


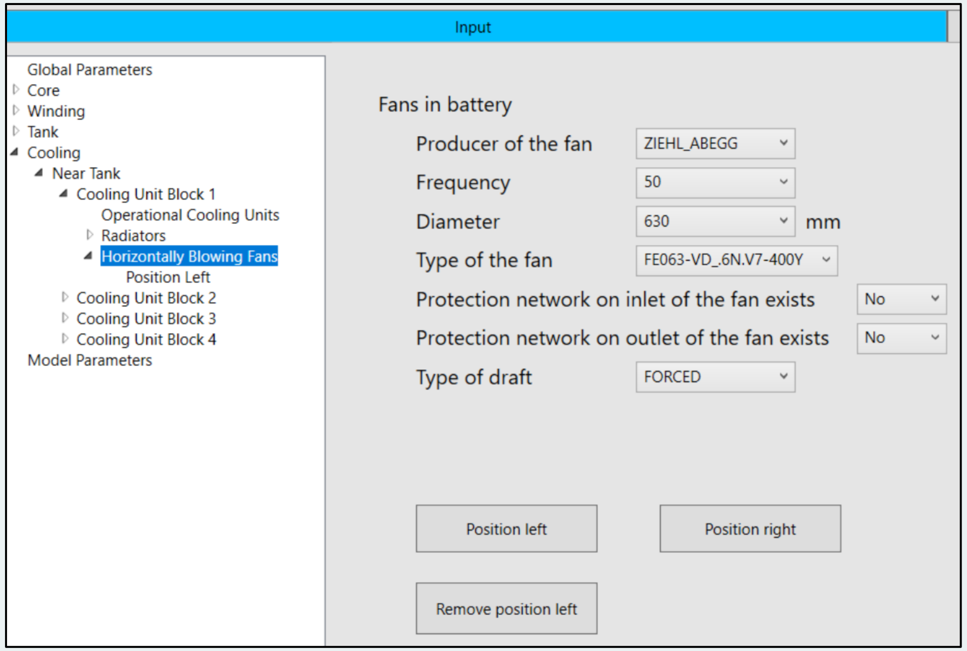



# Radiators / Fans

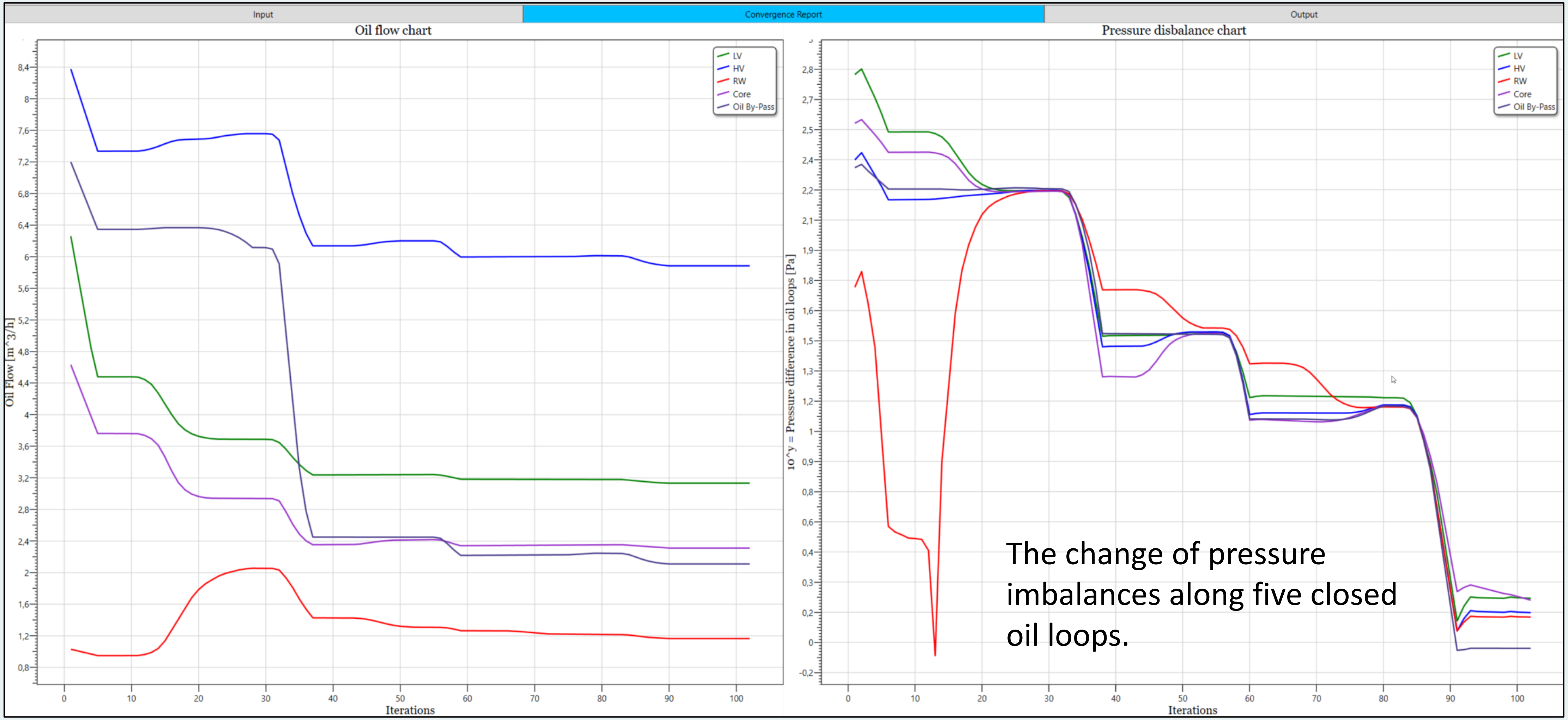



For the selected fan, retrieves characteristics (e.g., pressure–airflow curves). Determines air velocity based on pressure produced by fans vs. frictional pressure drop on the radiators.

# Numerical iterative process

Oil flow through five branches inside the tank is changing to balance the pressure in each of the inner branches with the pressure in the outer cooling branch. The flow through the outer cooling is equal to the sum of the flows inside the tank.




The change of pressure imbalances along five closed oil loops.

# Main results – Guarantee values

| OIL (COOLING SYSTEM) | Calculated | Limit |
|---|---|---|
| Top oil rise [K] | 48.4 | 65 |
| Average oil rise [K] | 32.33 | / |
| Bottom oil rise [K] | 16.26 | / |
| Gradient Top - Bottom [K] | 32.15 | / |

| WINDINGS | LV | HV | RW | Limit |
|---|---|---|---|---|
| Common Part | | | | |
| Average winding rise [K] | 43.58 | 43.05 | 34.32 | 80 |
| Hot spot rise [K] | 65.41 | 69.58 | 47.35 | 80 |

Calculated values for the core surface and the hot spot in the core

| CORE | Calculated | Limit |
|---|---|---|
| Surface temperature rise [K] | 70 | 90 |
| Hot spot temperature rise [K] | 84.52 | 90 |
| Frictional pressure drop [Pa] | 37 | / |
| Bottom oil temperature rise over ambient [K] | 16.94 | / |
| Top oil temperature rise over ambient [K] | 60.8 | / |
| Oil flow [m3/h] | 2.3115 | / |

# Main results – Intermediate values

The hot spot factor is determined from calculated hot spot temperature ($\vartheta_{hs}$), top oil temperature ($\vartheta_{to}$), average winding temperature ($\vartheta_{av}$), and average oil temperature ($\vartheta_{ao}$).

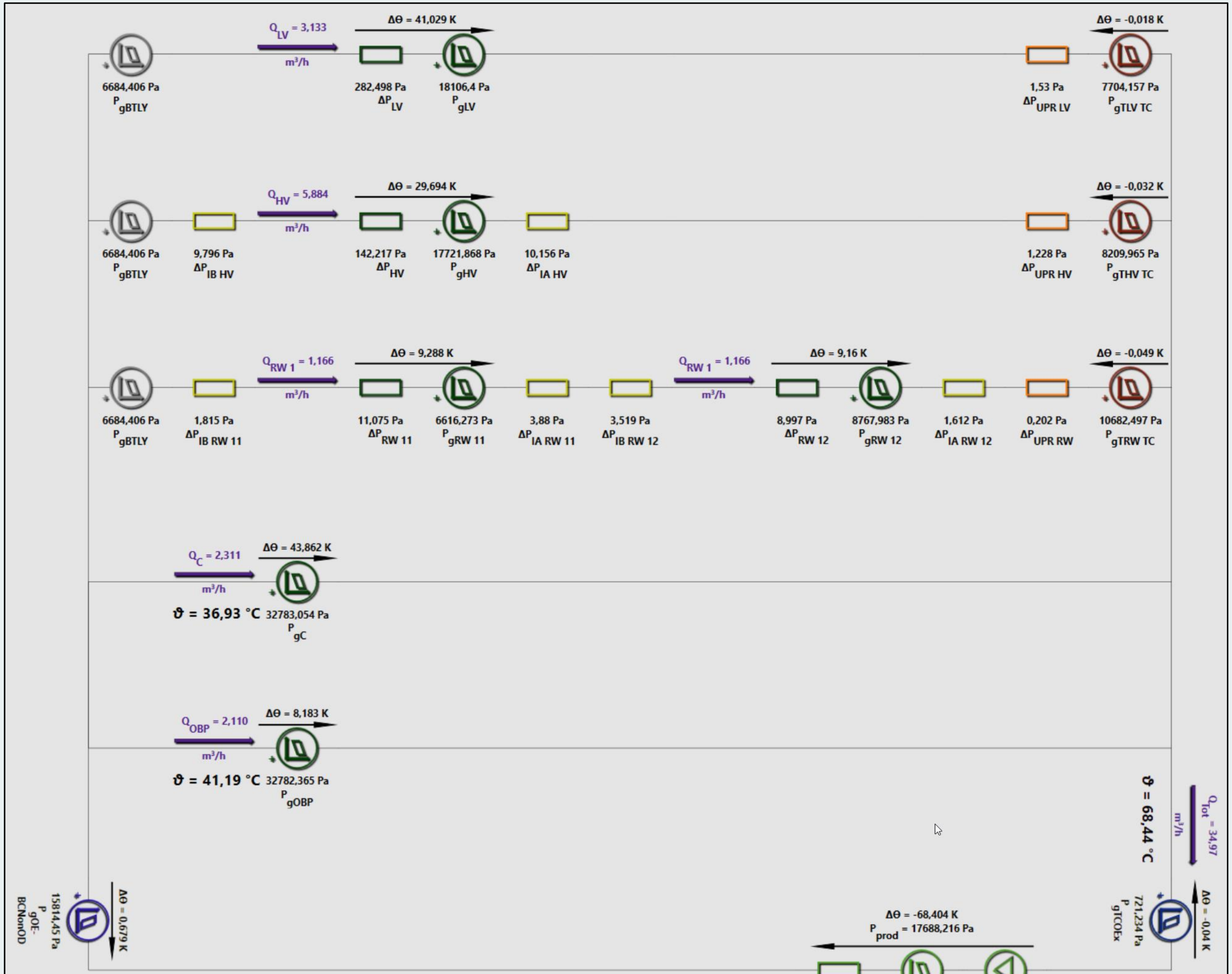
$$H = \frac{\vartheta_{hs} - \vartheta_{to}}{\vartheta_{av} - \vartheta_{ao}}$$

Two options for top oil:

- Oil entering the cooler
- Oil at the top of the winding

| WINDINGS | LV | HV | RW | Limit |
|---|---|---|---|---|
| Common Part | | | | |
| Average winding rise [K] | 43.58 | 43.05 | 34.32 | 80 |
| Hot spot rise [K] | 65.41 | 69.58 | 47.35 | 80 |
| Bottom oil temperature rise over ambient [K] | 16.94 | 16.94 | 16.94 | / |
| Average oil temperature rise over ambient [K] | 37.45 | 31.78 | 26.16 | / |
| Top oil temperature rise over ambient [K] | 57.96 | 46.62 | 35.38 | / |
| Oil flow per phase [m3/h] | 3.1329 | 5.8841 | 1.166 | / |
| Frictional pressure drop in winding [Pa] | 282 | 142 | 20 | / |
| Test-bay results (based on cooler oil temperatures) | | | | |
| Test-bay gradient [K] | 11.25 | 10.72 | 1.99 | / |
| Test-bay hot-spot factor | 1.51 | 1.98 | -0.53 | / |
| Calculated results (based on winding oil temperatures) | | | | |
| Calculated gradient [K] | 6.13 | 11.27 | 8.16 | / |
| Calculated hot-spot factor | 1.22 | 2.04 | 1.47 | / |
| Other Parameters | | | | |
| Oil flow / heat loss parameter | 2.4326 | 3.4138 | 5.5025 | / |
| Average oil - Average cooling system oil [K] | 5.12 | -0.55 | -6.17 | / |
| Average radial oil velocity [cm/s] | 1.6 | 0.7 | 0.3 | 10 - 50 |
| Min radial oil velocity [cm/s] | 1.1 | 0.2 | 0.1 | 1 |
| Max radial oil velocity [cm/s] | 4.4 | 1.3 | 0.7 | 50 |
| Max axial oil velocity [cm/s] | 5.6 | 6.4 | 1.2 | 75 |
| Pressure drop top end insulation [Pa] | 0 | 10.2 | 5.5 | / |
| Pressure drop bottom end insulation [Pa] | 0 | 9.8 | 5.3 | / |

# Hydraulic Scheme




Oil flows and characteristic oil temperatures for all five inner branches and the outer cooling branch.

# The pressure drops on the elements of the branches

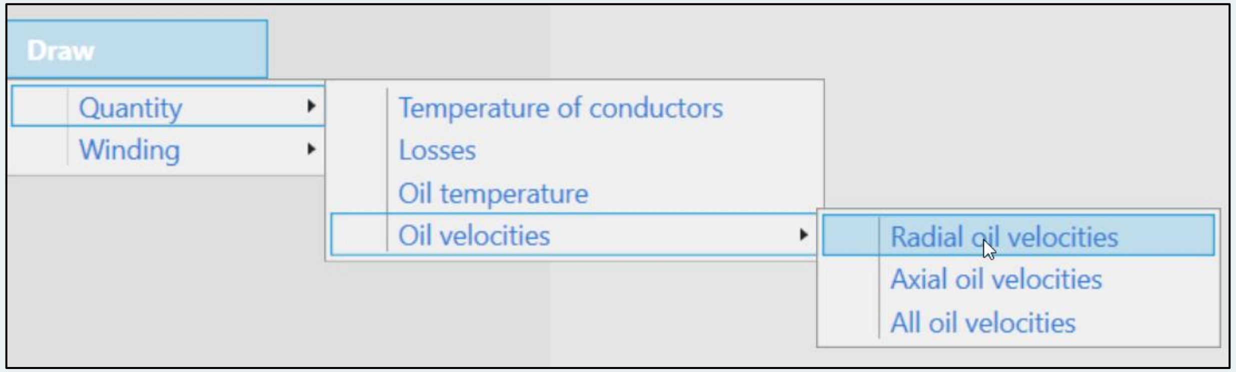

An example for the high voltage winding, consisting of:

- Between the bottom tank and the top of the yoke (gravitation)
- Insulation below the winding
- Winding itself
- Insulation above the winding
- Path of oil under the pressing ring
- Between the winding top and the top of the core (gravitation)

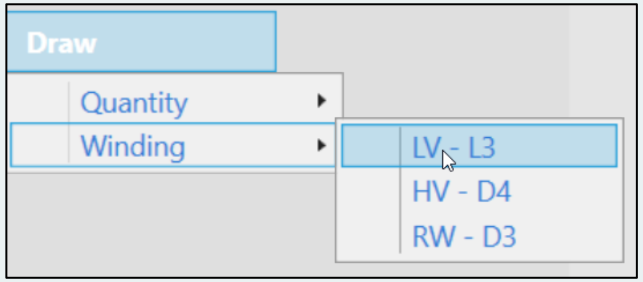
# Winding calculation results

Drawing options:

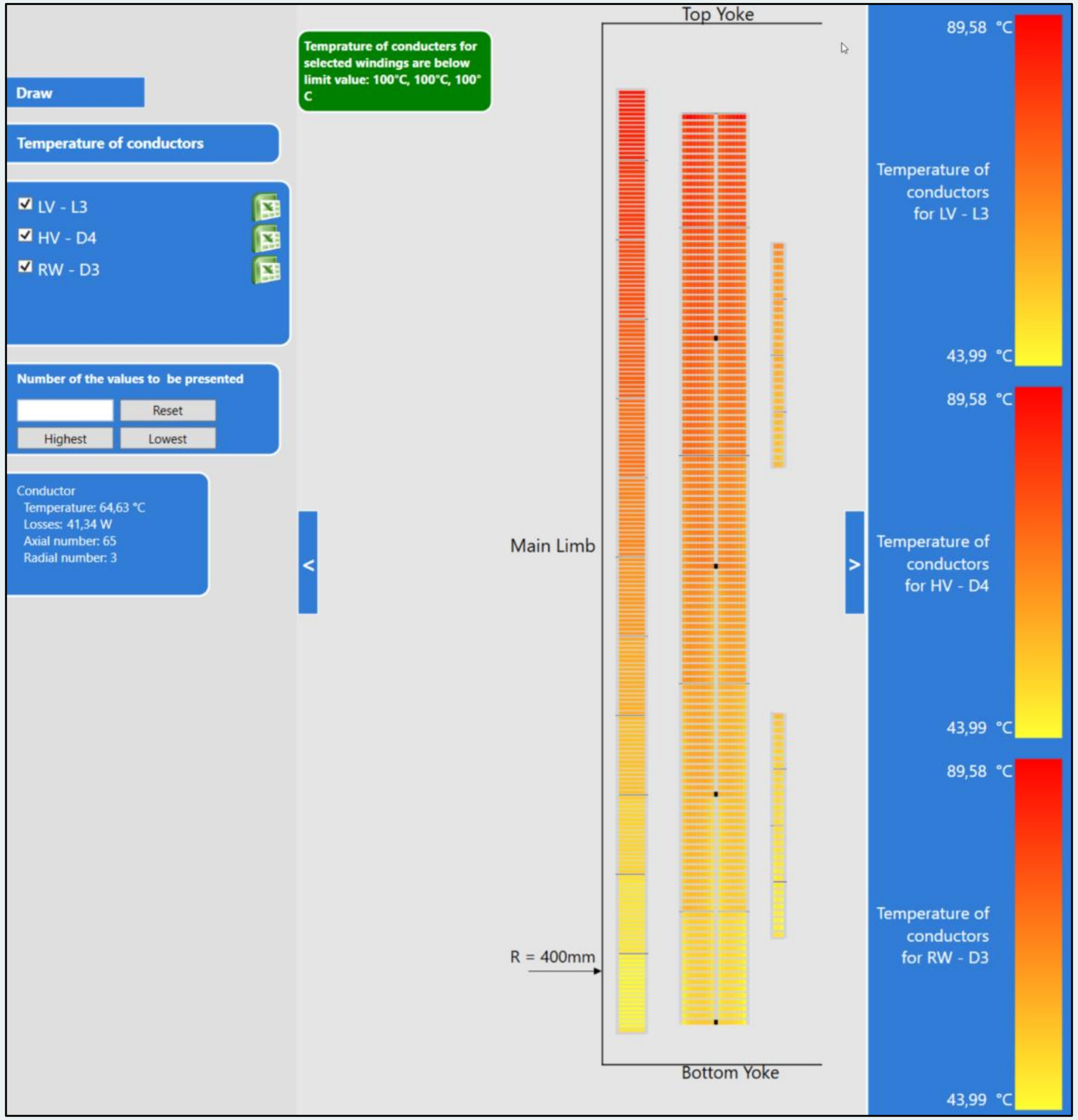
- One quantity (temperature of conductors, losses, oil temperatures, and oil velocities) for all the windings




- One of the windings and observe selected quantities for it



# Temperatures for conductors for all windings

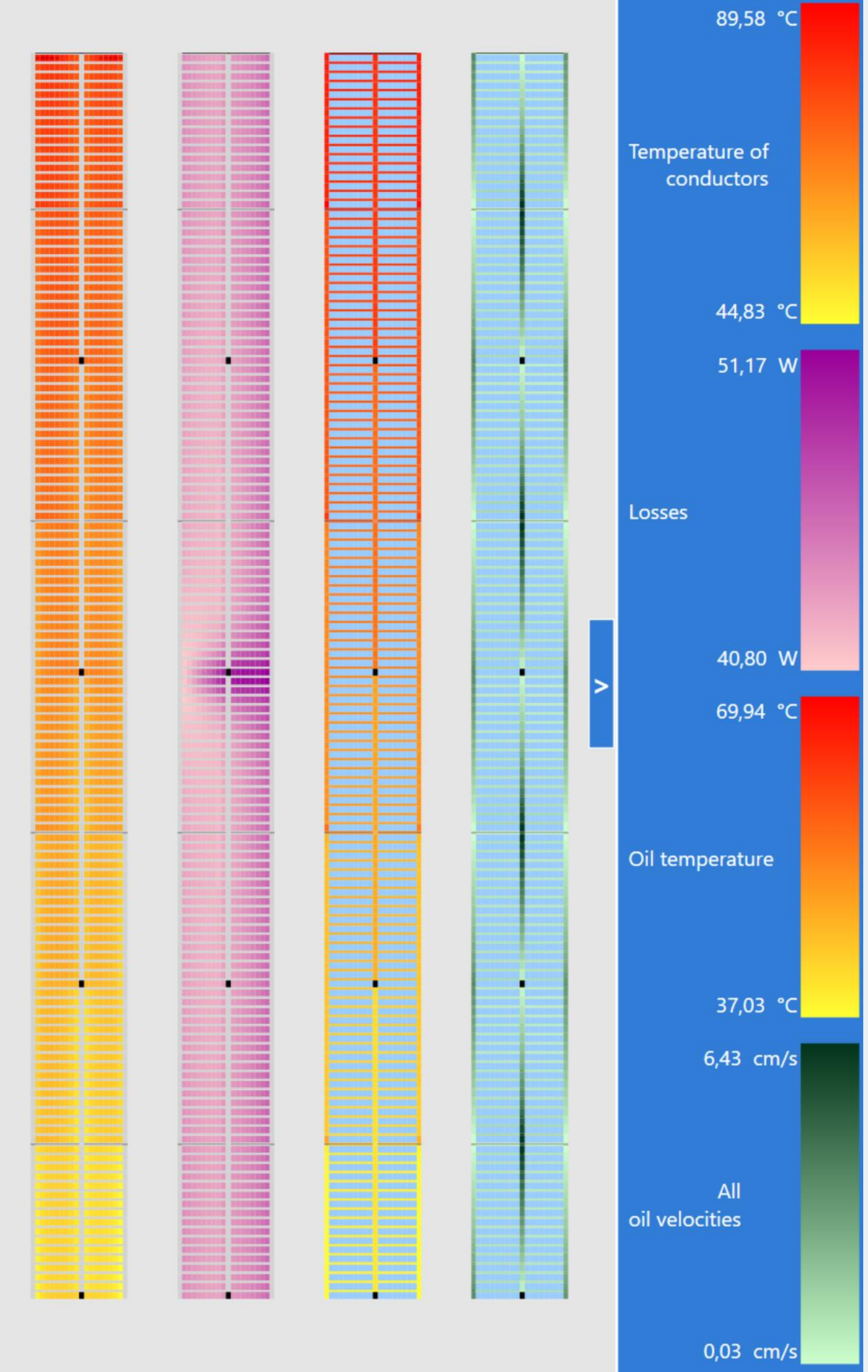


# The hottest conductors

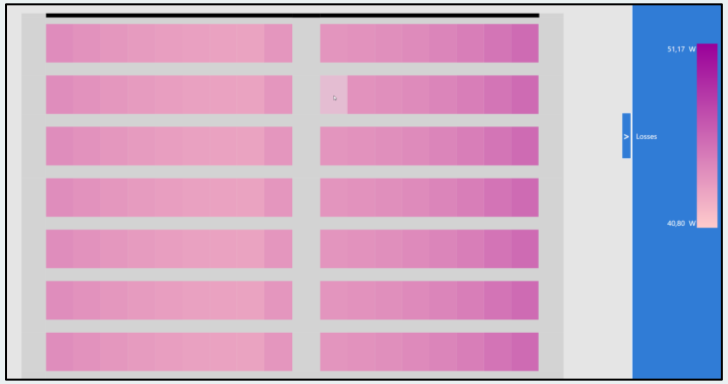

Critical insights:

- F.O. sensor positioning
- Locating zones for detailed analyses to improve design if needed

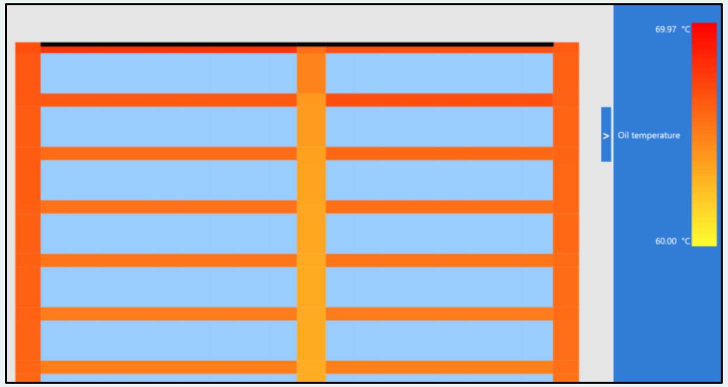
# Drawing all quantities for the HV winding



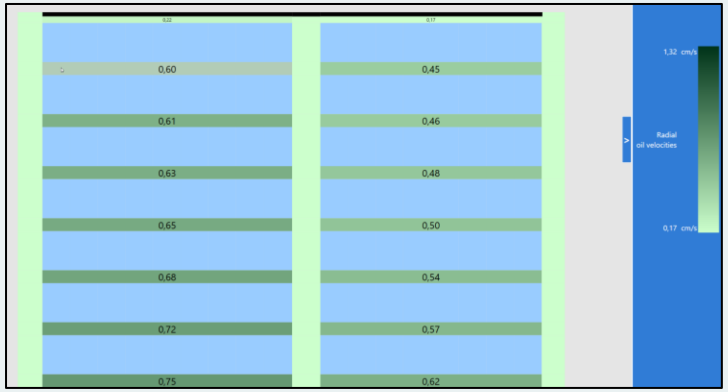
# Exploring the zone with the highest temperature in HV winding




Losses




Oil temperature



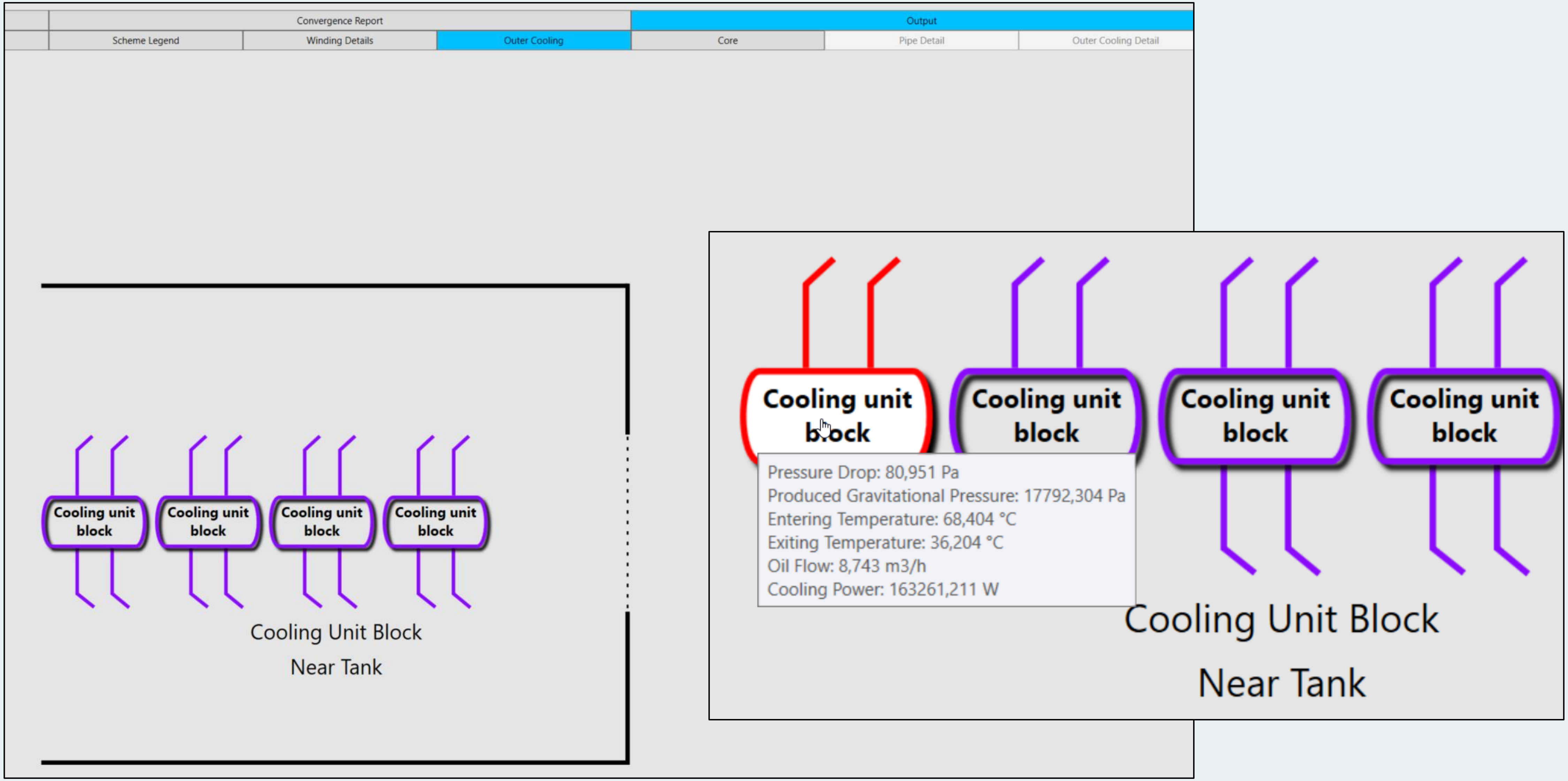

Radial duct oil velocity

In this sample case, the highest temperatures appear in the inner part of the top coil.

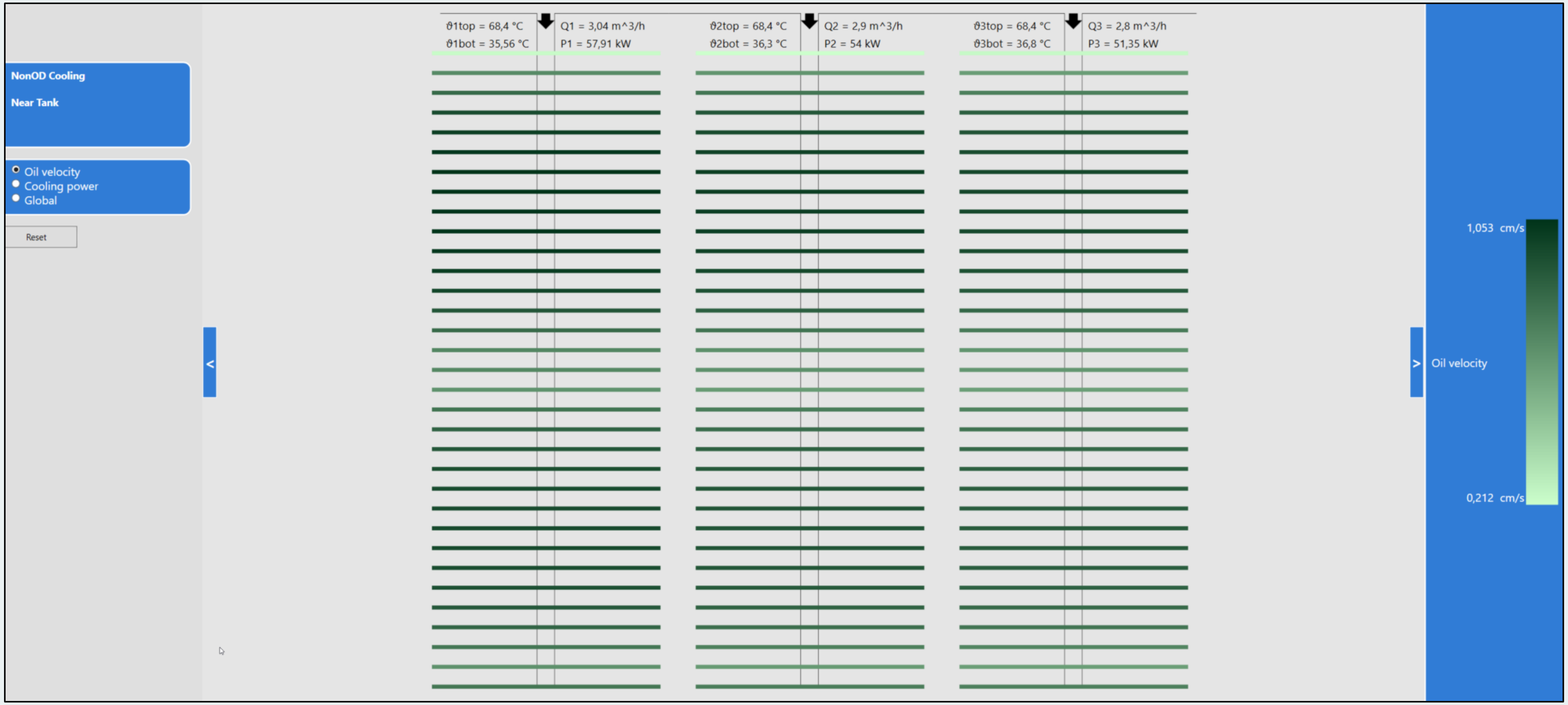
The following factors influence the temperature distribution:

- The duct above the coil is smaller than other ducts, influencing the flow through this duct to be small. The velocity in this radial duct is 0.22 cm/s, while in the others you can see the values 0.61, 0.62 cm/s and so on.
- This low oil flow caused a lower heat transfer coefficient, and consequently, higher temperatures in this coil.
- The oil flows from the inlet to the radial duct to the outlet, increasing its temperature.
- The conductor near the inner axial duct is cooled on the axial surface near the axial duct.

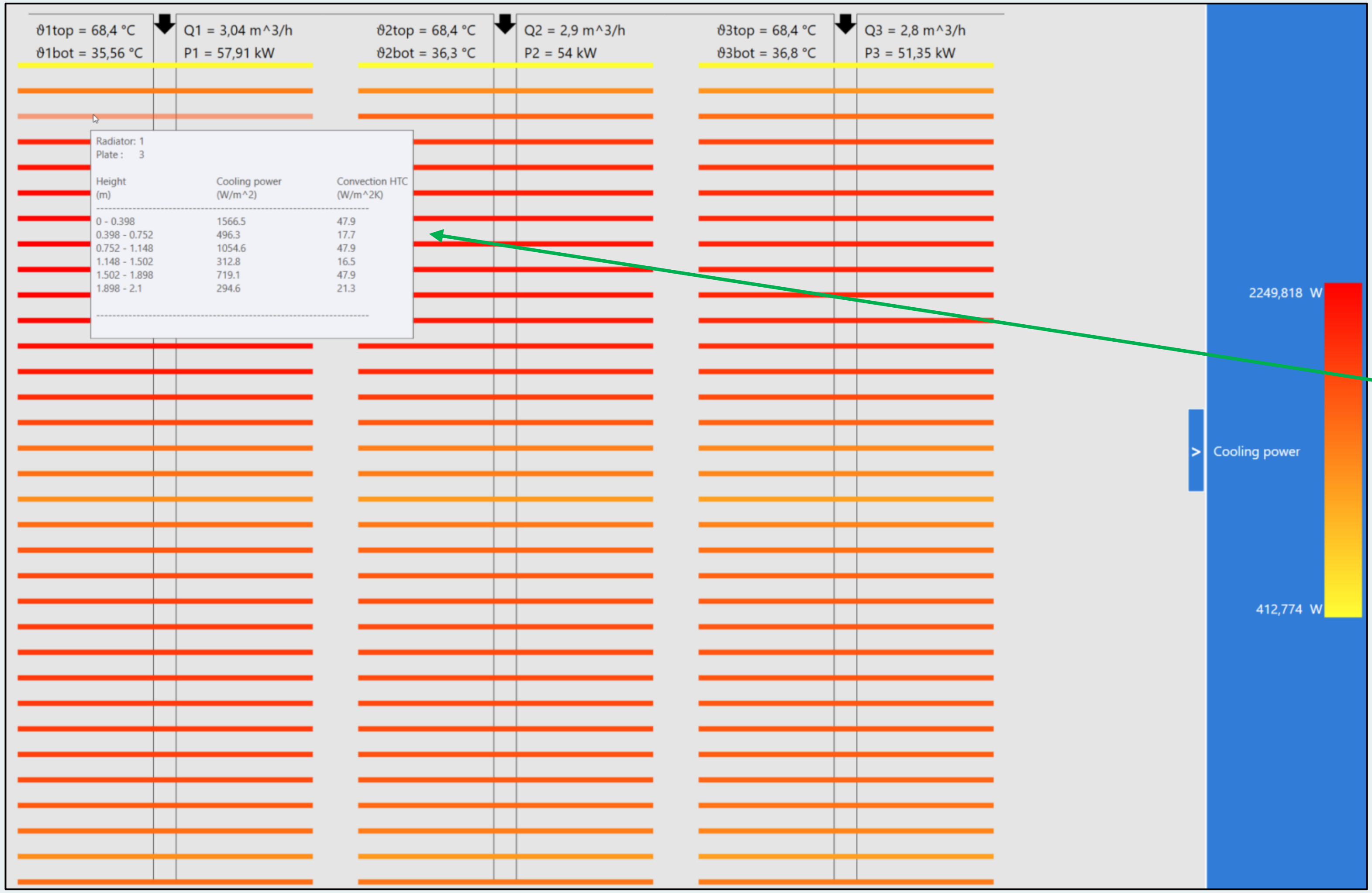
# Outer cooling results



# Cooling unit block 1 – Oil velocity distribution

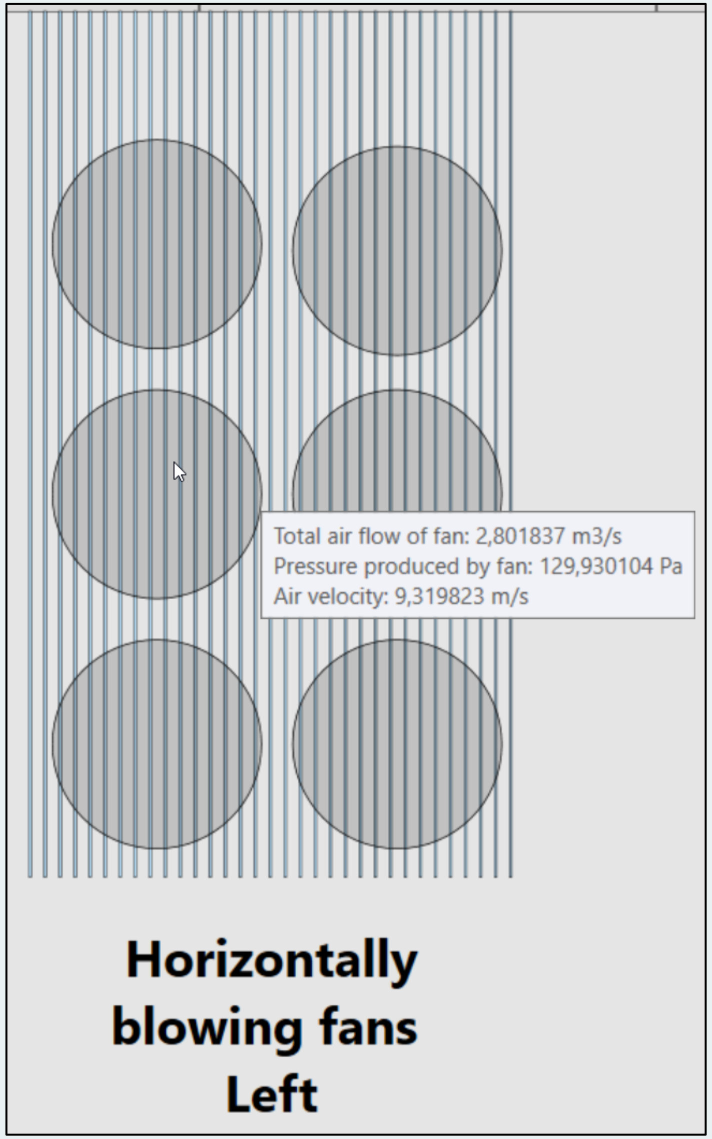


# Cooling unit block 1 – Cooling power distribution




Details of the cooling power in AF and AN zones in each of the plates can be observed.

# Values calculated for the fan




**End of the text related to Static HoST**

# Transition from Static to Dynamic HoST

- Intensive work on dynamic THNM began in 2022, requiring major changes in the thermal model.
- Incorporates distributed heat accumulation modeling via a 1D convective-diffusive partial differential equation:

$$c_p \frac{\partial(t,X)}{\partial t} + \rho c_p u(t,X) \cdot \nabla(t,X) + \nabla\big(-k\nabla(t,X)\big) = q_v$$

- Hydraulic calculations in dynamic THNM remain similar as those in the static THNM. A component for dynamic pressure drop due to changes in oil flow velocity over time is added.
- We published the basics of the model, for example in [6] and [7]

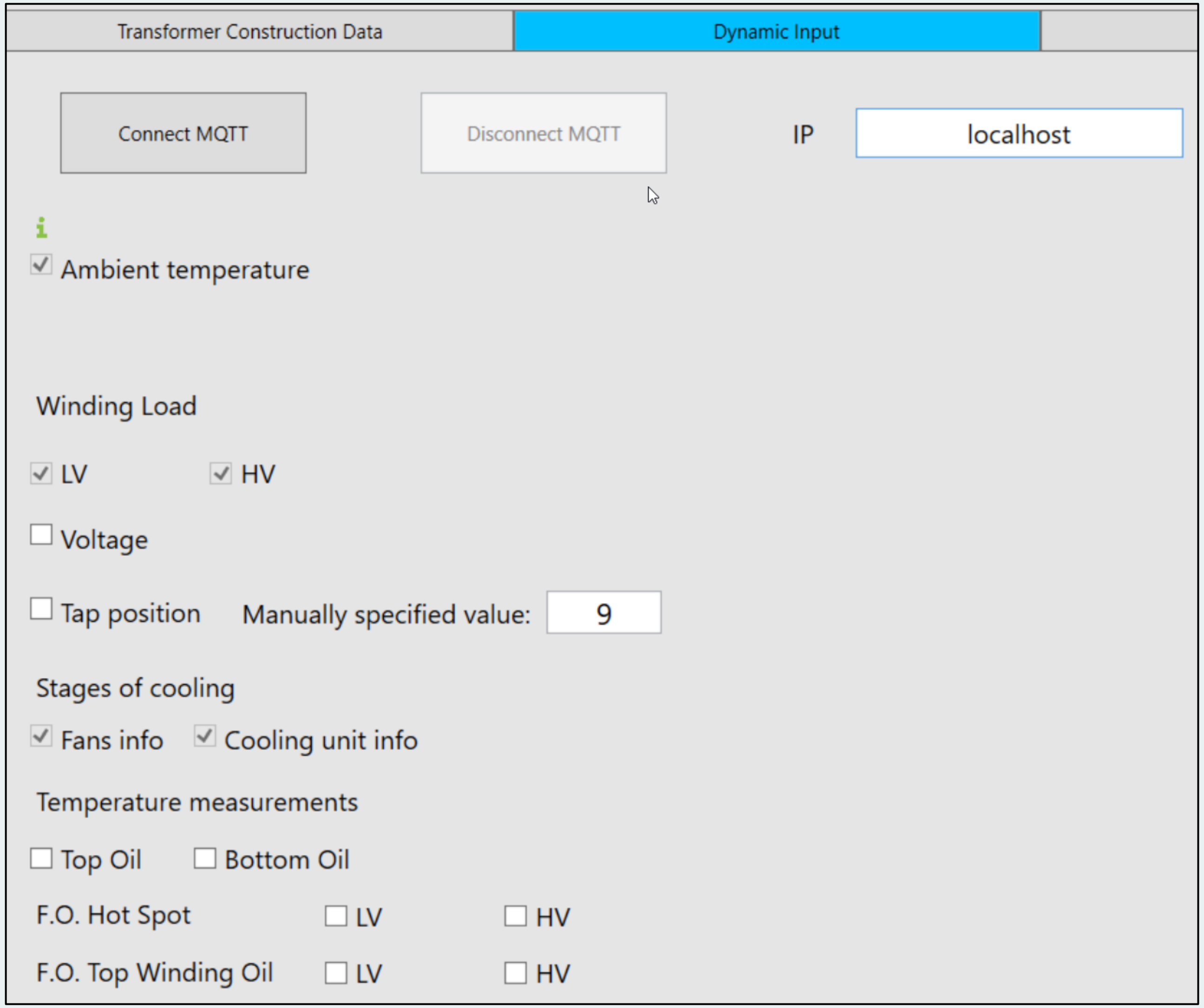
# Input data for dynamic THNM

- The same set of data as for Static HoST

  (detailed transformer construction data and material properties)

- The main Dynamic HoST application mode is to calculate the temperatures in the transformer's on-line grid operating mode
- The data from the operation are needed (Dynamic HoST contains a module for collecting data via internet communication using the MQTT protocol)
- The program collects data from PT for a period of 1 minute, and temperatures and flows are calculated for 1 minute into the future

# Data from transformer grid operation




Necessary data:

- ambient temperature
- load for each winding
- tap position
- fan information
- cooling unit information

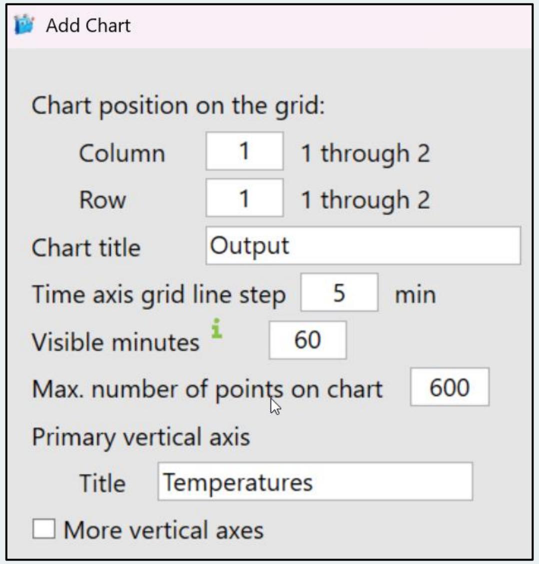
The remaining data is optional.

The data set is transmitted via MQTT messages.

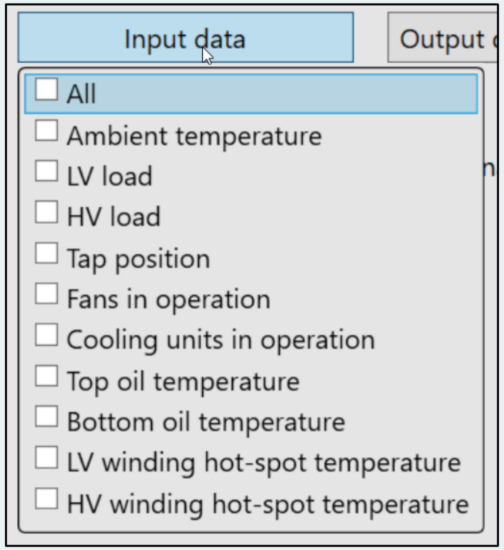
The software receives and processes MQTT messages, performs range validation of the values, and resolves situations when information about a specific operational variable is interrupted.

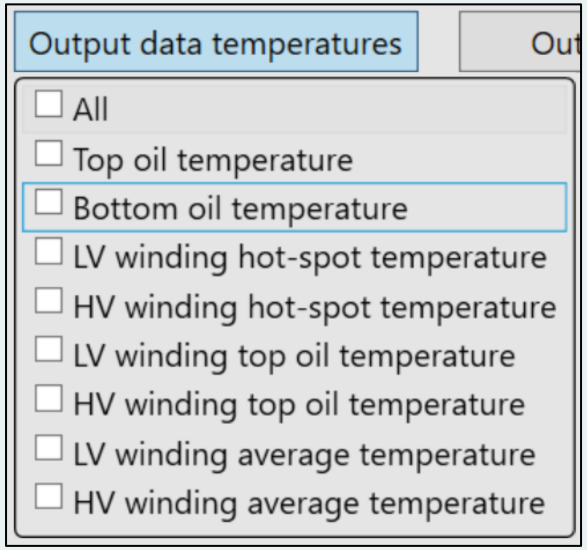
# Generating charts of values change over time

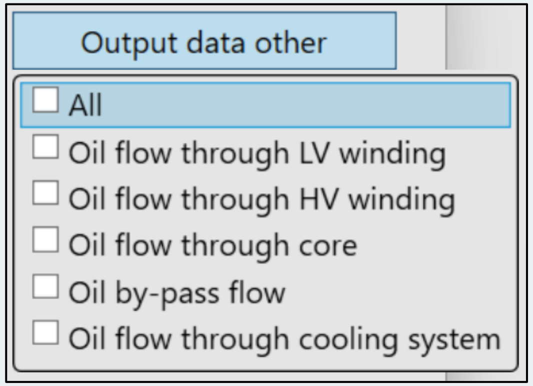
Configuring charts



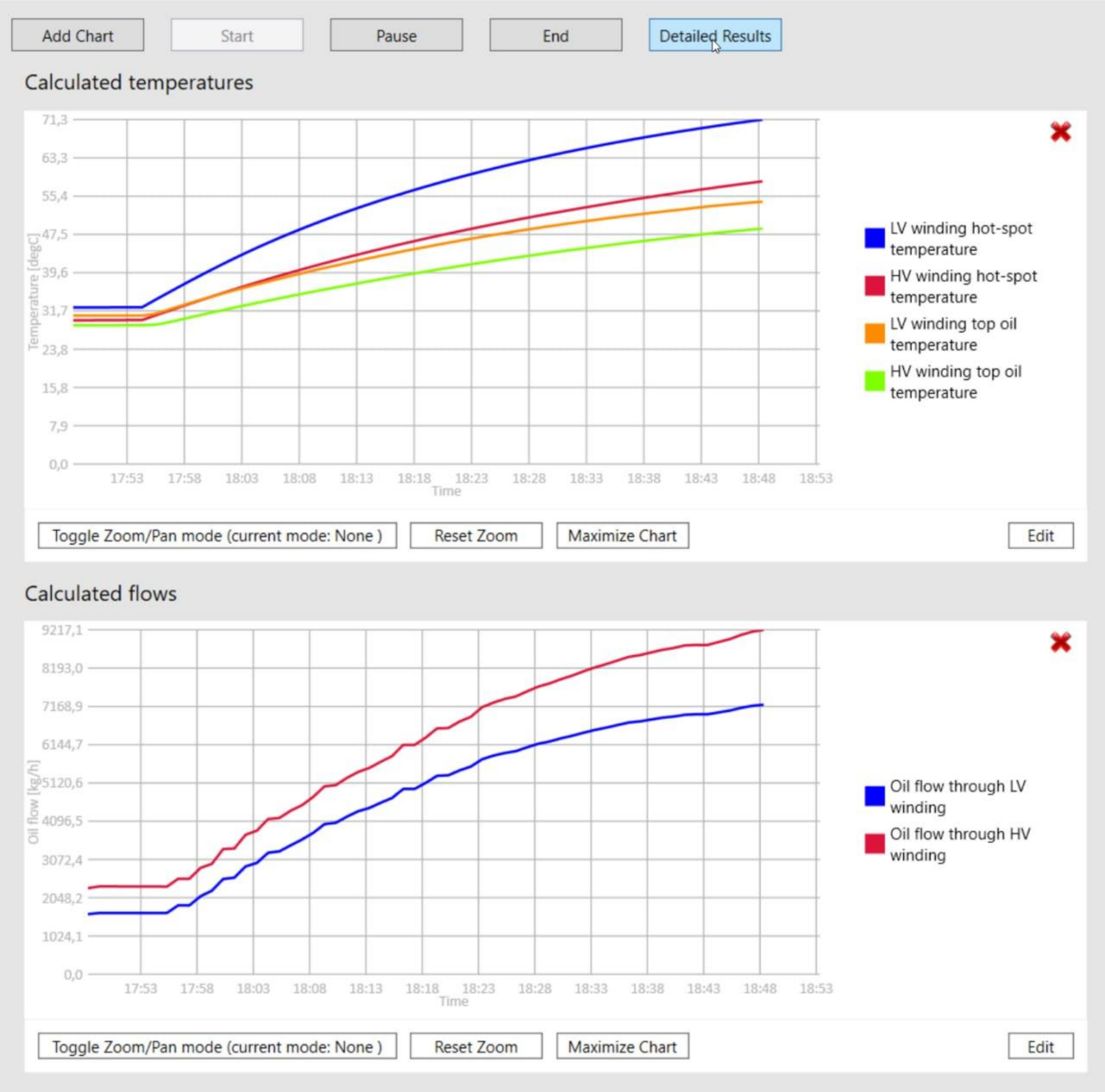

Selecting the data presented on the charts



# Live charts

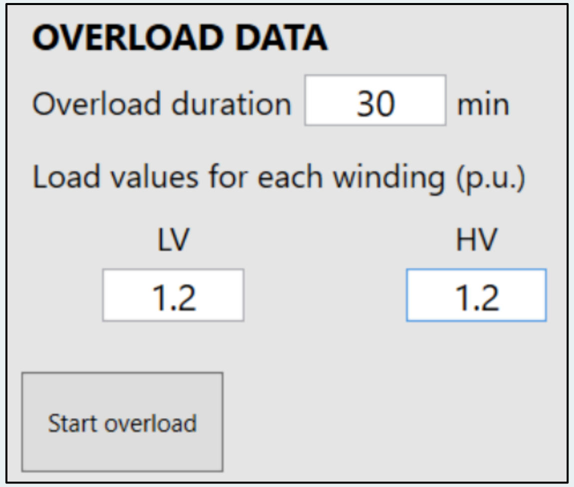



All values available in Static HoST output GUI can be seen in Dynamic HoST at a frozen moment, by clicking on the Detailed Results button.

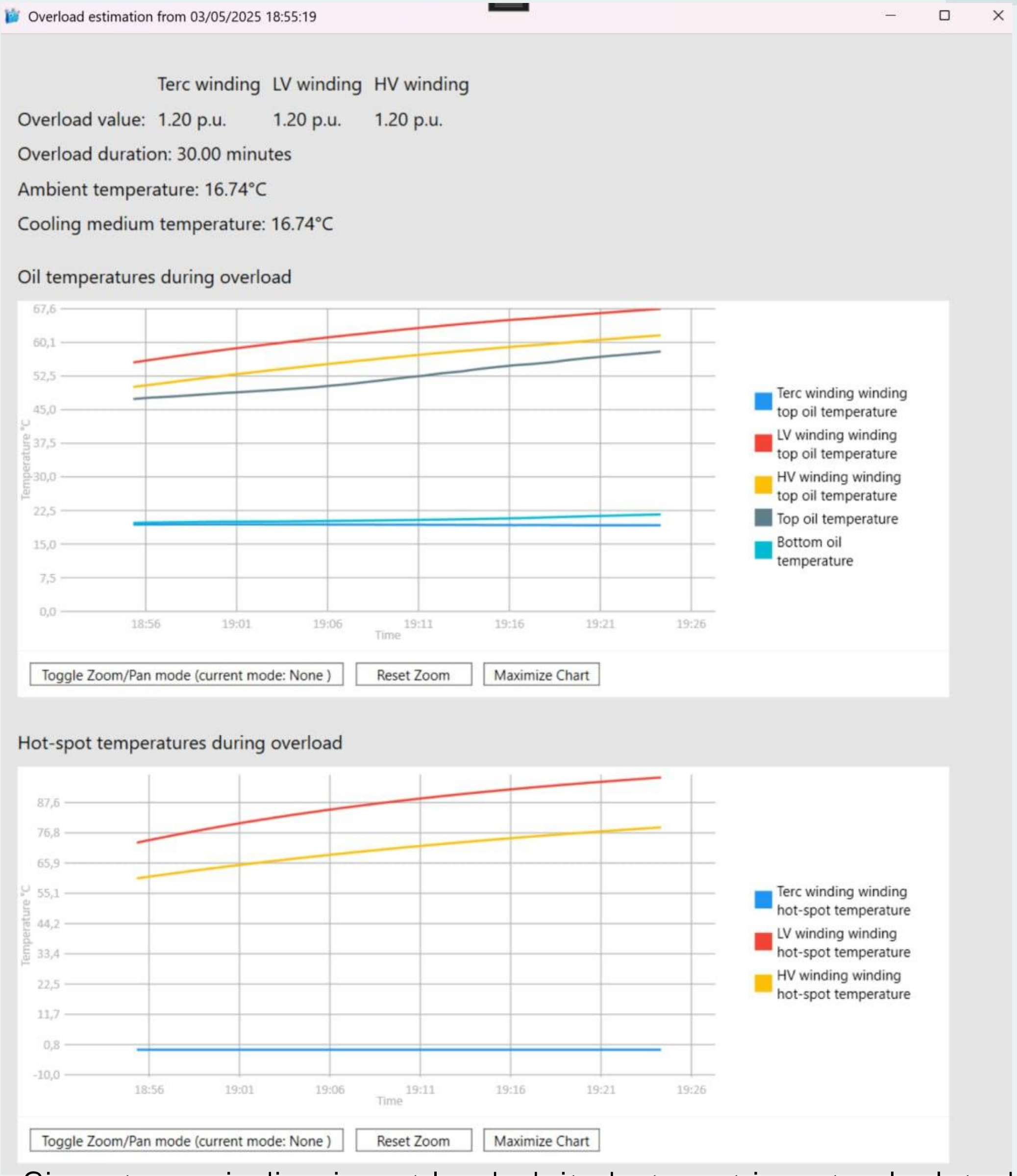
# Assessment of the overload possibility

This can be done at any moment during grid operation.

Specifying overload




After clicking on the Start overload button, a separate parallel thread is created, and calculation for the specified overload is performed.




Since terc winding is not loaded, its hot-spot is not calculated.

# Key Features & Capabilities of Dynamic HoST

- Cold Start Simulation:
  - Accurately predicts the highest insulation temperature during cold start.
- Real-Time Adaptability:
  - Considers changes in load, ambient temperature, fan operation, cooling unit status, and tap position.
- Advanced Applications:
  - Can be used for training Reduced Order Models (ROM), machine learning (ML), or neural network models (NN), or for parametrization of simple models.

# History & Evolution of HoST Calculus

- We published the paper about the basics of static THNM in 2010 in IEEE Trans. on Power Delivery (Reference [2]) and kept working on further development.
- Applications of the model are presented in [3], [4] and [5].
- Meantime static THNM and its software implementation reached a high level of technological readiness.
- Static HoST is now used in design departments in several factories.
- We continuously provide thermal calculations and consulting services for checking and improving the design.
- We began intensively working on dynamic THNM in 2022.
- The results of first validation of dynamic THNM are published in [7].

# Conclusion and Key Benefits

- Accurate Thermal Modeling:
  - Achieve precise predictions to ensure transformer reliability and safety.
- Design Optimization:
  - Integrate comprehensive data analysis to optimize transformer design and performance.
- Efficient Calculations:
  - Fast processing enables quick decision-making during design and operation.
- Real-Time Monitoring:
  - Dynamic HoST’s real-time capabilities support predictive maintenance and investment planning.

# Illustrative publications since the first paper in 2008


1. Radakovic, Z., Sorgic, M. (2008): Wirtschaftliche Betrachtung der thermischen Auslegung von ölgekühlten Leistungstransformatoren, Elektrizitätswirtschaft, Jg 107, Heft 15, 32-38
2. Radakovic, Z., Sorgic, M. (2010): Basics of Detailed Thermal-Hydraulic Model for Thermal Design of Oil Power Transformers, IEEE Trans. on Power Delivery, Vol. 25, No. 2, 790-802
3. M. Sorgic, Z. Radakovic. (2010): Oil-Forced Versus Oil-Directed Cooling of Power Transformers, IEEE Trans. on Power Delivery, Vol. 25, No. 4, 2590-2598
4. Radakovic, Z., Sorgic, M., Van der Veken, W., Claessens, G. (2012): Ratings of Oil Power Transformer in different Cooling Modes, IEEE Trans. on Power Delivery, Vol. 27, No. 2, 618-625
5. Radakovic, Z., Radoman, U., Kostić, P. (2015): Decomposition of the Hot-Spot Factor, IEEE Trans. on Power Delivery, Vol. 30, No. 1, 403-411 (DOI: 10.1109/TPWRD.2014.2352039
6. Novkovic, M., Radakovic, Z., Torriano, F., Picher, P. (2023), Proof of the Concept of Detailed Dynamic Thermal-Hydraulic Network Model of Liquid Immersed Power Transformers, Energies, 28. April, 2023, Volume 16, No. 9, 3808 (DOI: 10.3390/en16093808)
7. Novkovic, M., Torriano, F., Picher, P., Radakovic, Z. (2024): Application of Dynamic Detailed Thermal Hydraulic Model on a Transformer with zig-zag winding scale model, IEEE Trans. on Power Delivery, Vol. 39, No. 6, pp. 3338 - 3346. (DOI: 10.1109/TPWRD.2024.3466297)