Master’s thesis: Establishment of reasonable model to simulate emergency passive coolant system in HTTR reactor

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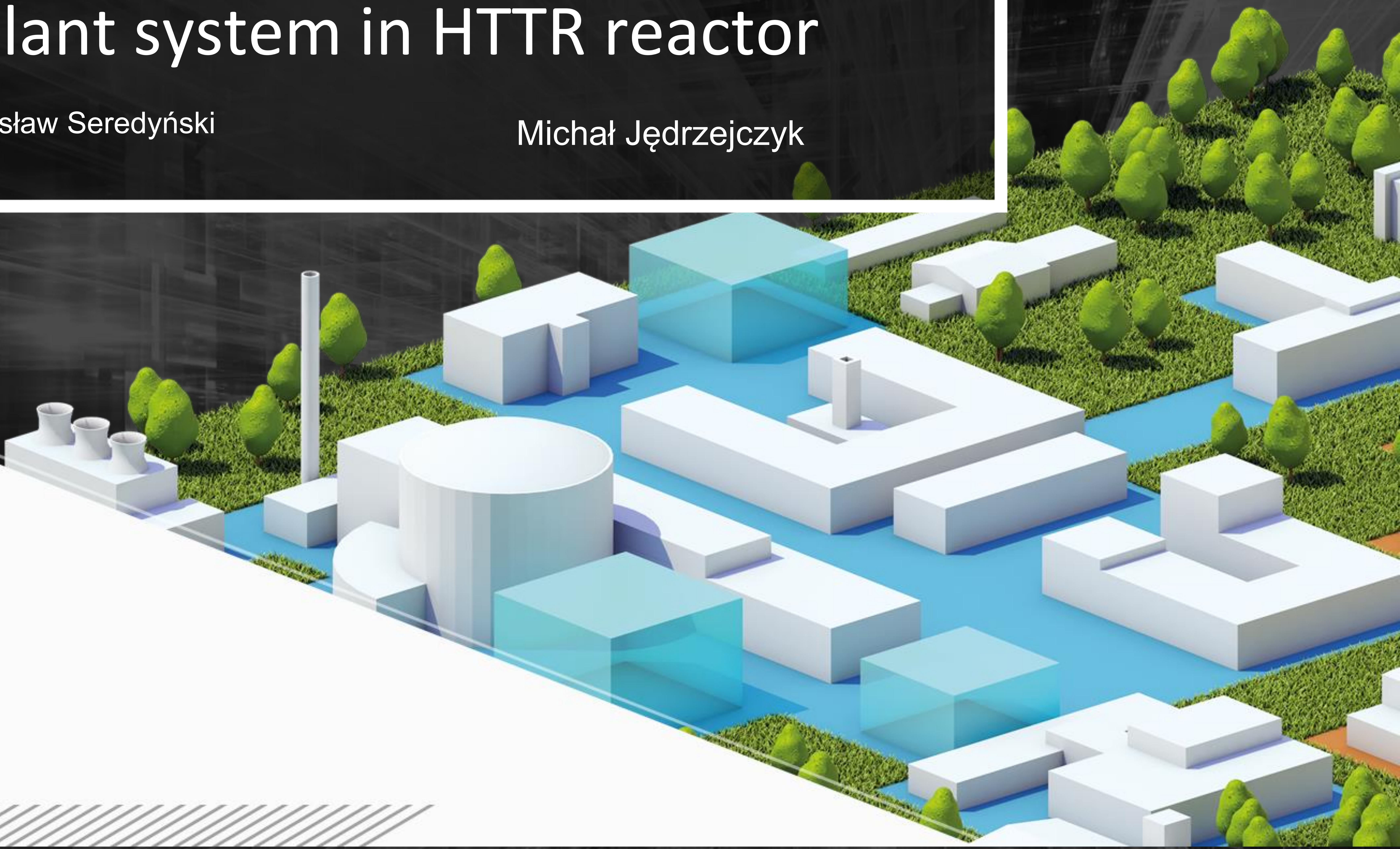
Michał Jędrzejczyk



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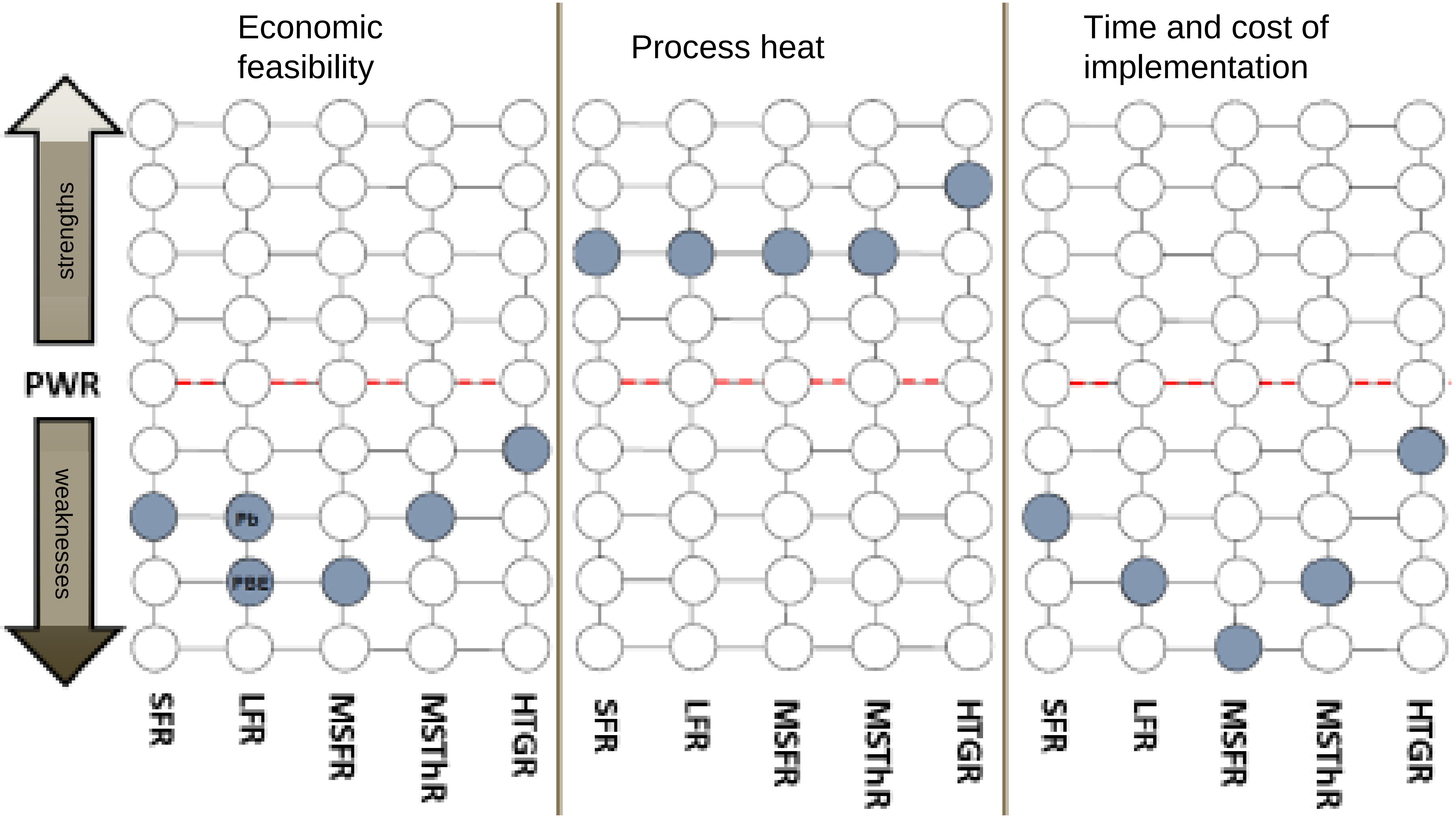
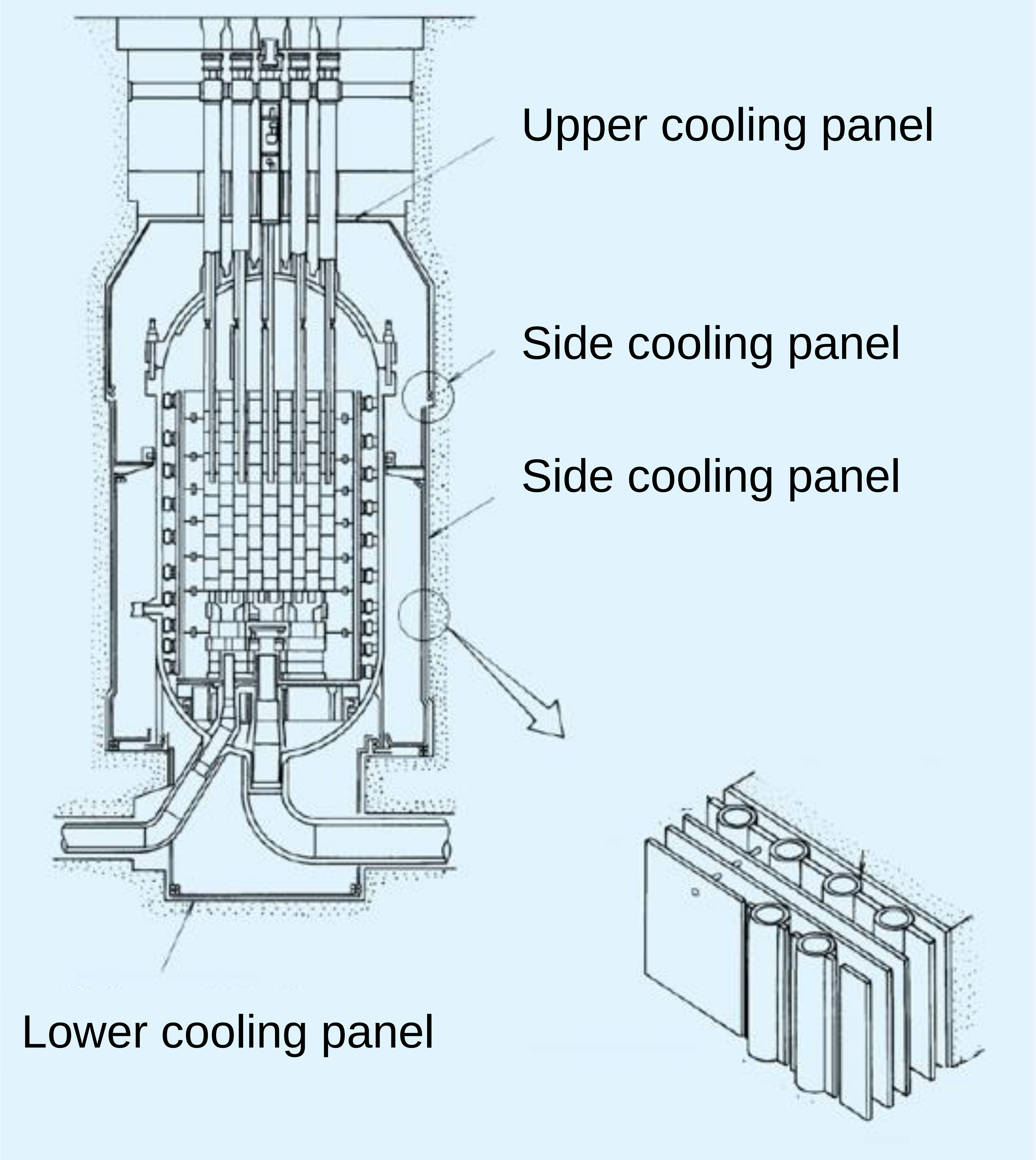
Most important element of thesis: developing calculation method allowing to simulate a two-fluid system with significantly reduced calculational cost

Reactor type comparison

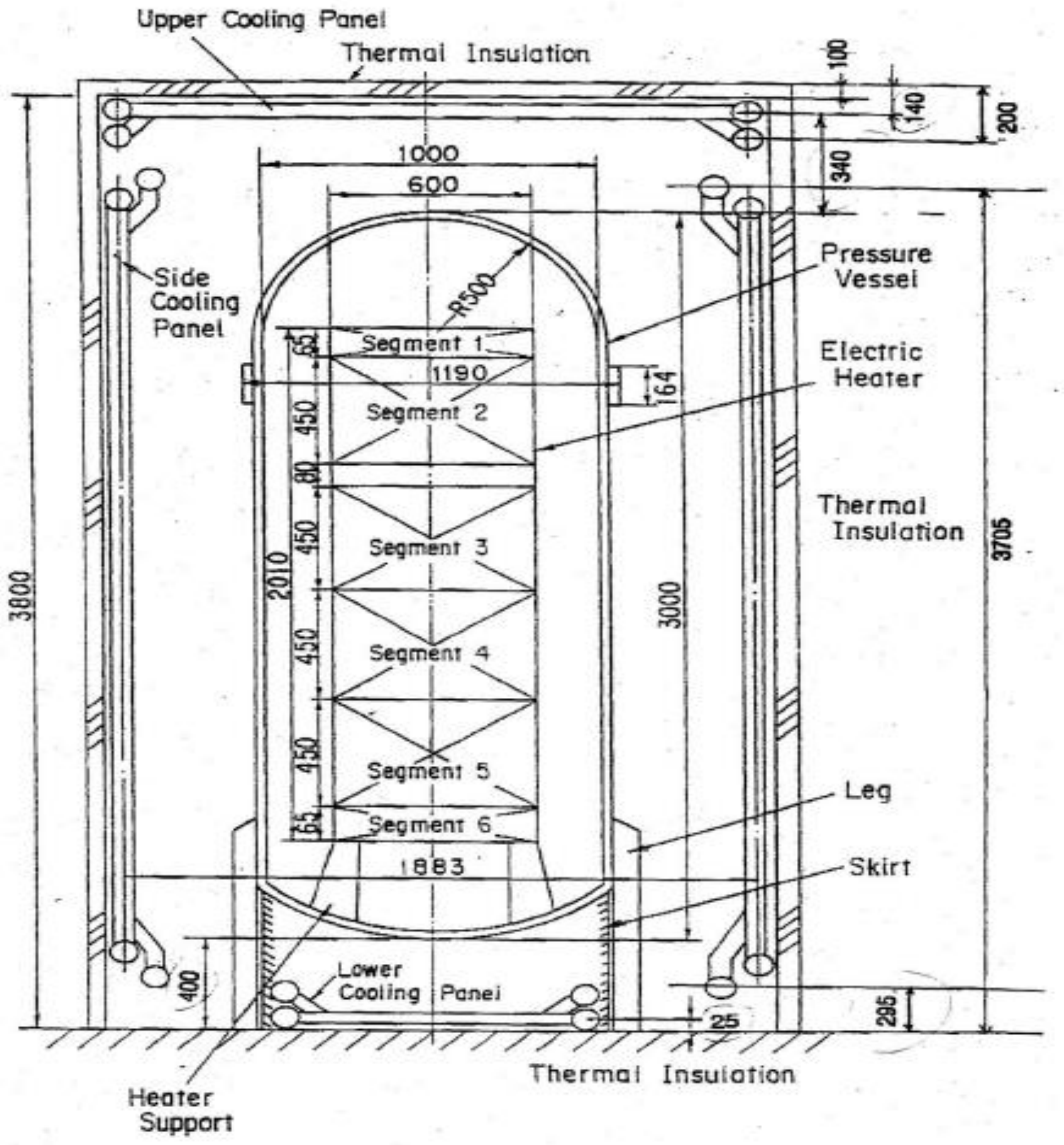


Comparison of available nuclear energy systems, Gregg Butler, Manchester University

High Temperature Test Reactor in Japan cross section



Benchmark experiment setup



Experimental setup drawing

Configuration number		I	II	III
Atmosphere inside the pressure vessel		Vacuum	He	N_2
Pressure [MPa]		$1,3 \cdot 10^{-6}$	0,73	1,1
Total heat power [kW]		13,14	28,79	93,93
Power generated in segments [kW]	No. 1	1,01	1,16	5,90
	No. 2	2,31	3,11	16,05
	No. 3	2,64	3,52	19,88
	No. 4	2,46	5,10	22,24
	No. 5	3,76	10,42	22,13
	No. 6	0,96	5,49	7,72
Cooling medium		Water	Water	Water

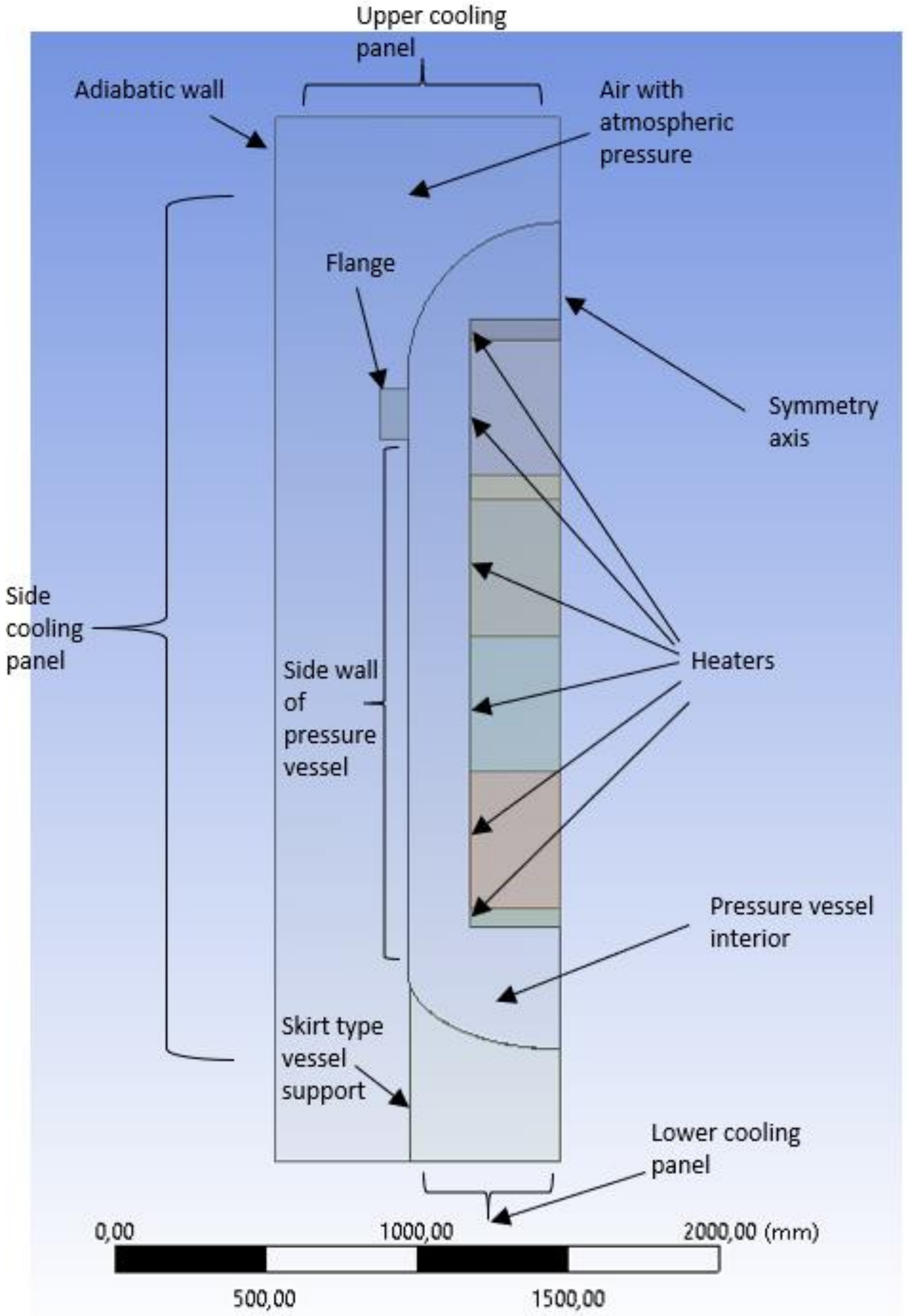
Conditions, under which the experiment was conducted

Source: Nuclear Power Technology Development Section, IAEA, Heat Transport and Afterheat Removal for Gas Cooled Reactors Under Accident Conditions, Vienna, 2000.

General assumptions for model

- Gas density as a function of temperature
- 2D axisymmetric geometry
- Volumetric heat generation on heaters
- Constant temperature boundary condition in place of cooling panels
- Turbulent flow between the vessel and cooling panels (Ra~10^9), RNG k-epsilon model with enhanced wall treatment

Geometry of model for configuration No. 1

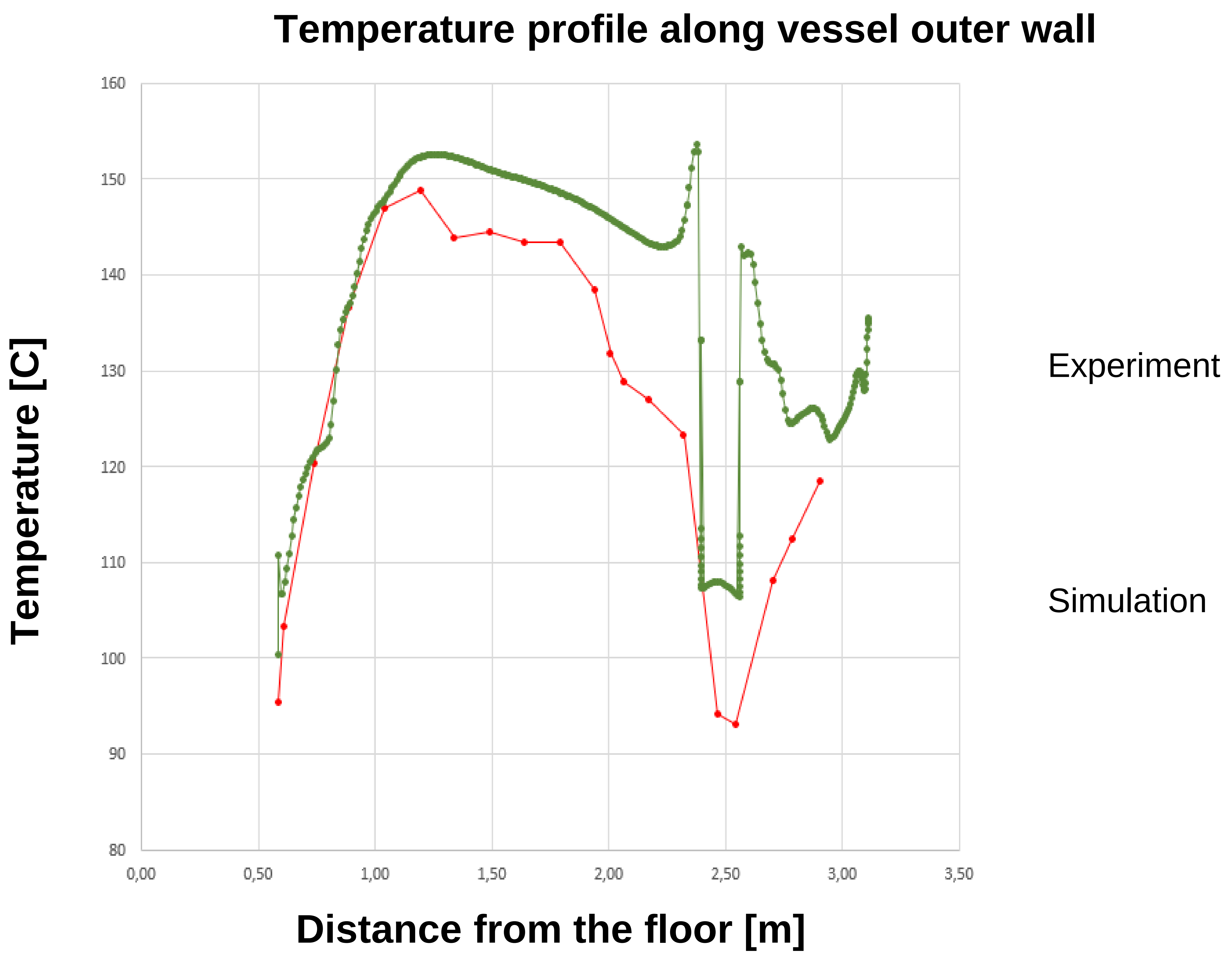


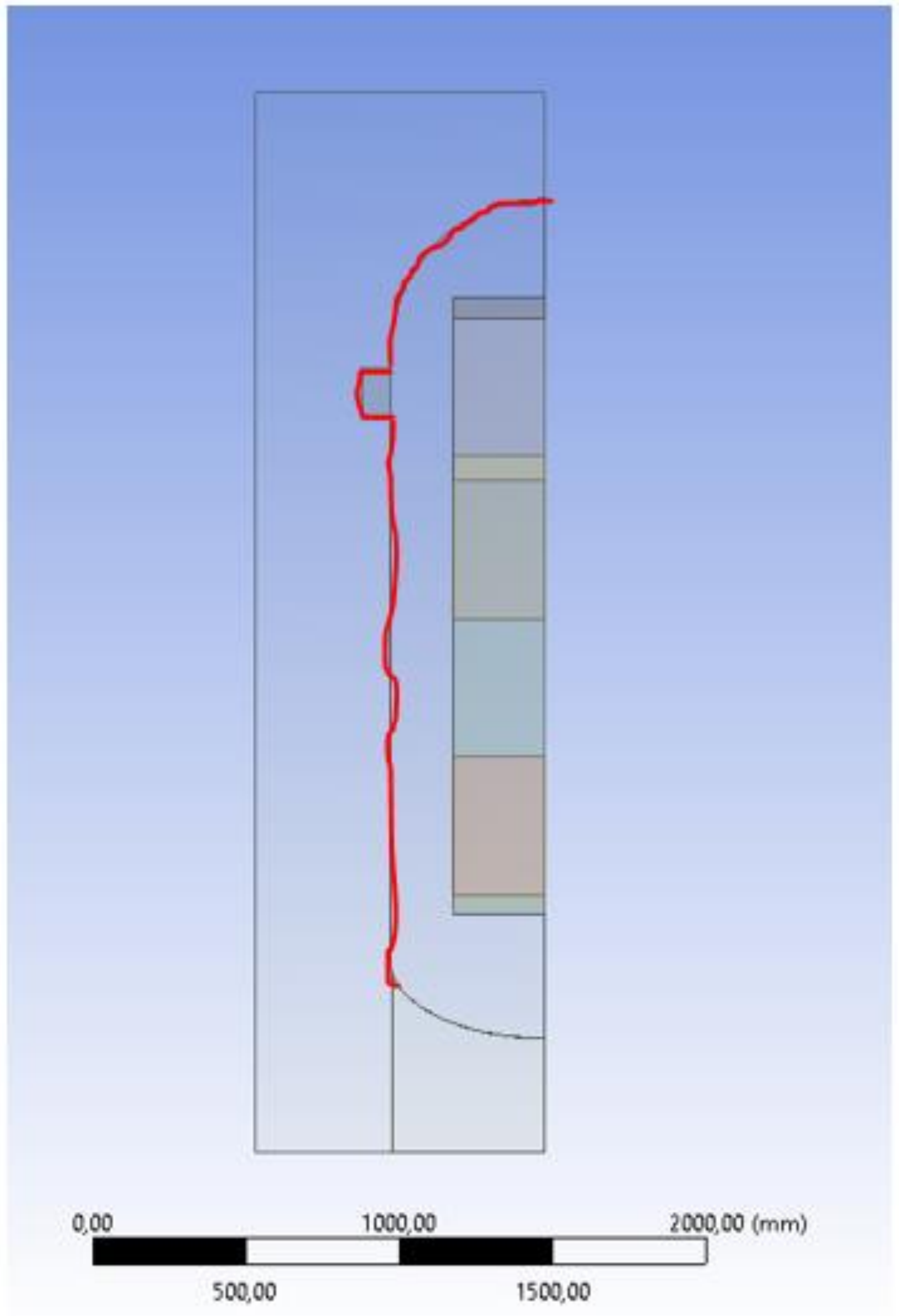
- Vessel interior pressure = 1 Pa
- Ra ~ 0 -> natural convection processes can be omitted in vessel interior
- Natural convection processes cannot be omitted in vessel surroundings
- Material properties taken from the experiment description published by IAEA

Mesh of model for configuration No. 1

Results for configuration No. 1

Configuration number		I
Gas inside the pressure vessel		Vacuum
Pressure [MPa]		$1{,}3 \cdot 10^{-6}$
Total heating power [kW]		13,14
Heating power of particular segments [kW]	No. 1	1,01
	No. 2	2,31
	No. 3	2,64
	No. 4	2,46
	No. 5	3,76
	No. 6	0,96
Cooling medium		Water



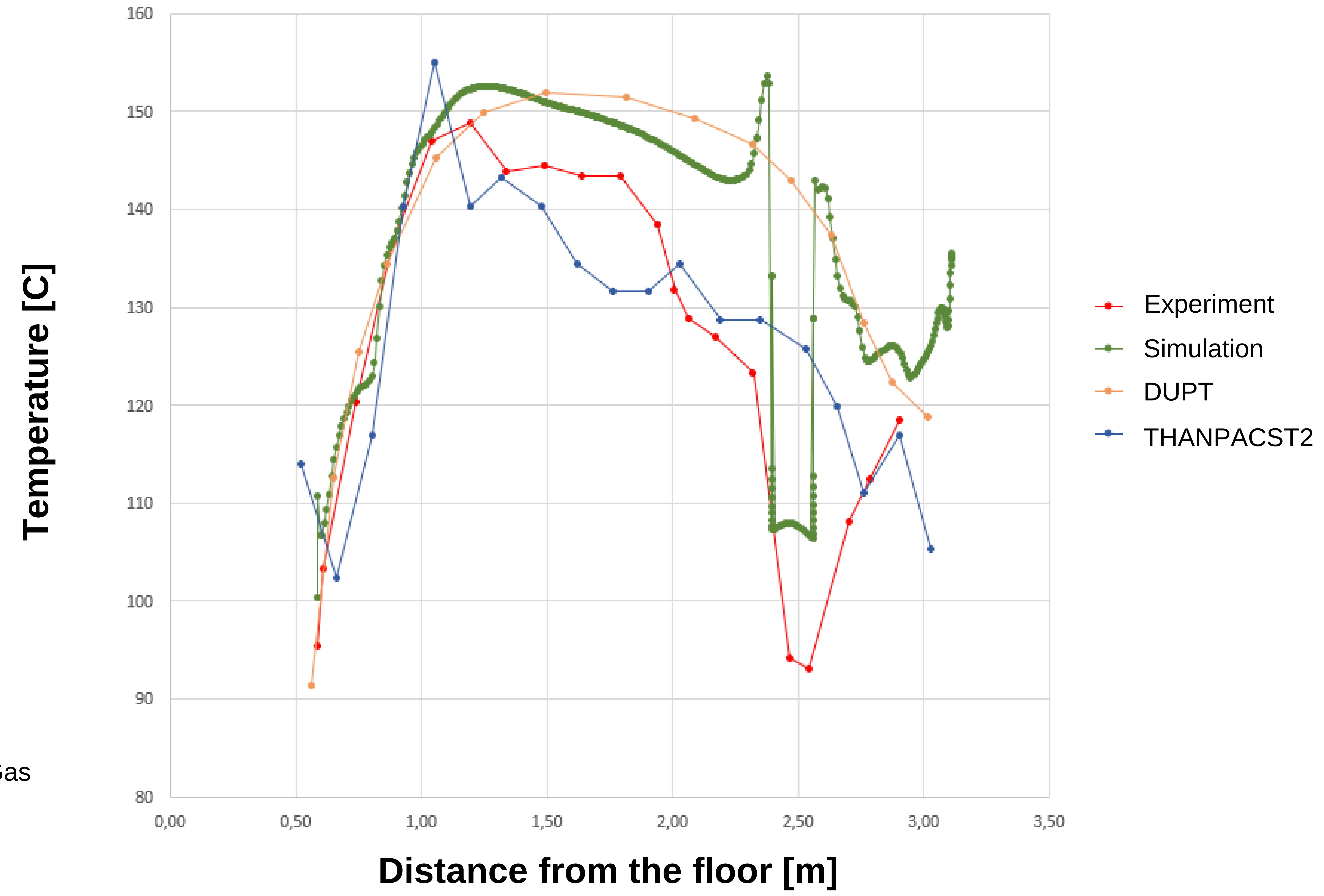


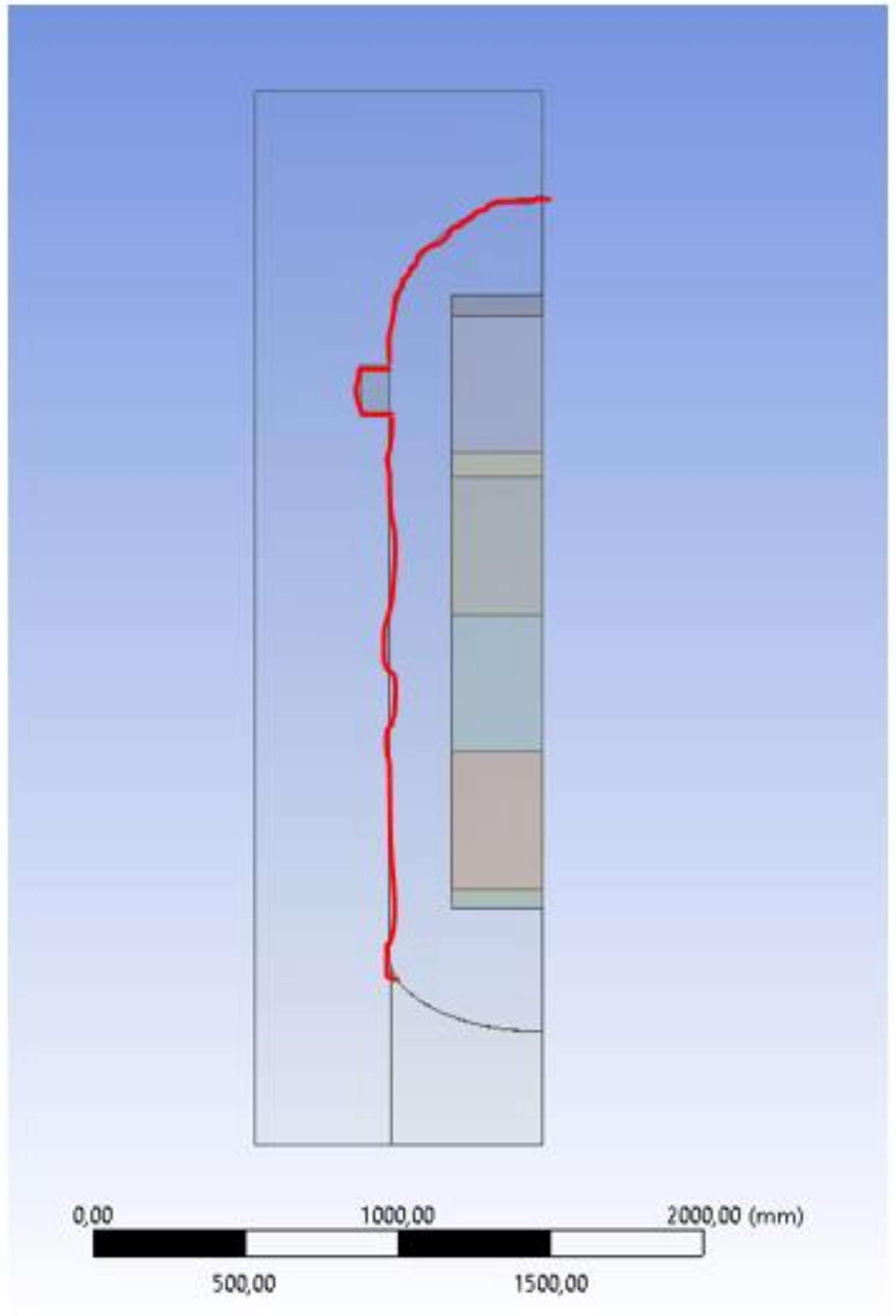
Results are in good agreement with the experiment (0-5% relative difference) except for the area close to flange up to 15 % relative difference.

Temperature spikes in the flange area are probably a result of simplifying local geometry

Comparison of results with results from another researchers

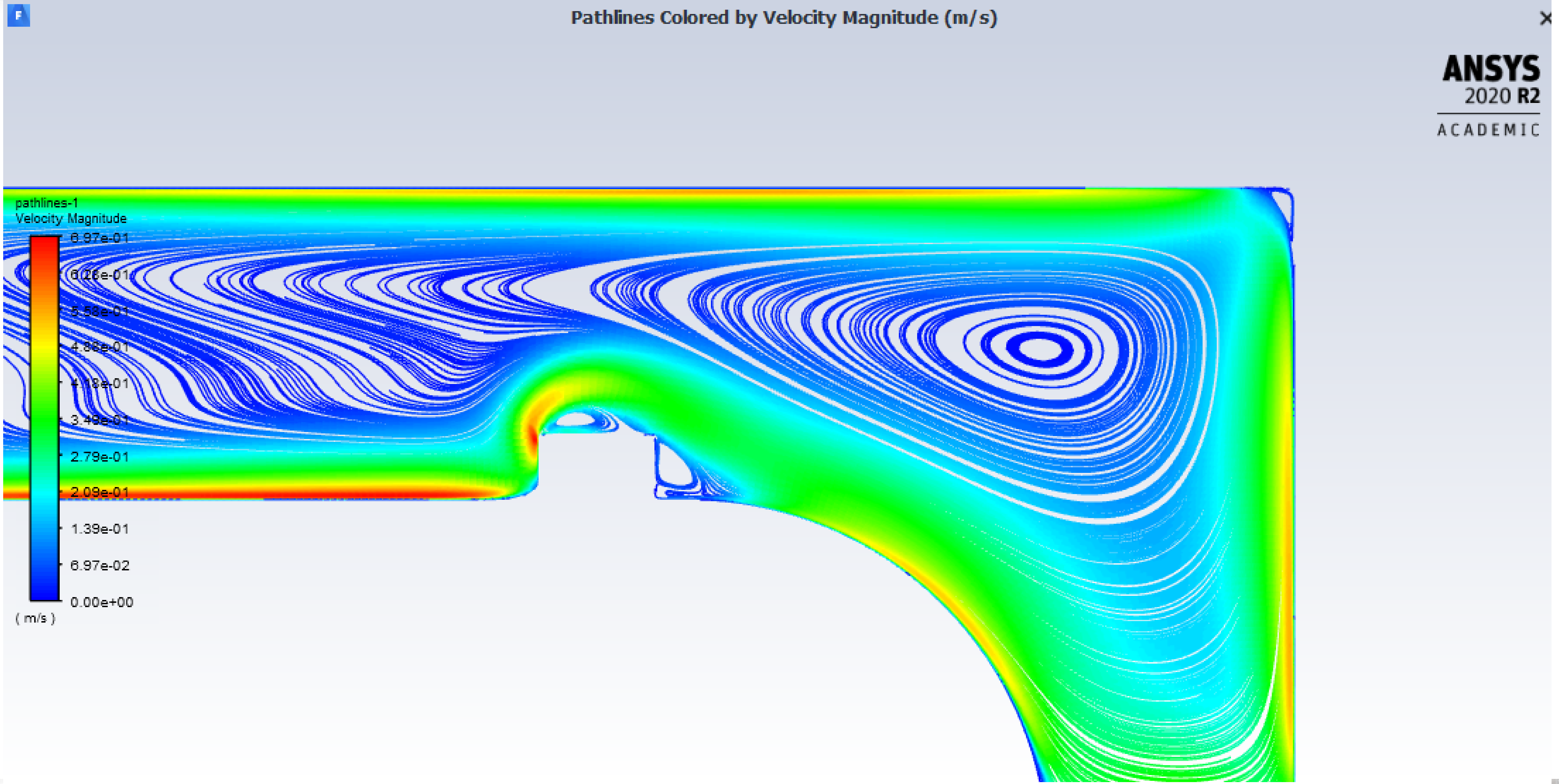
Temperature profile along vessel outer wall



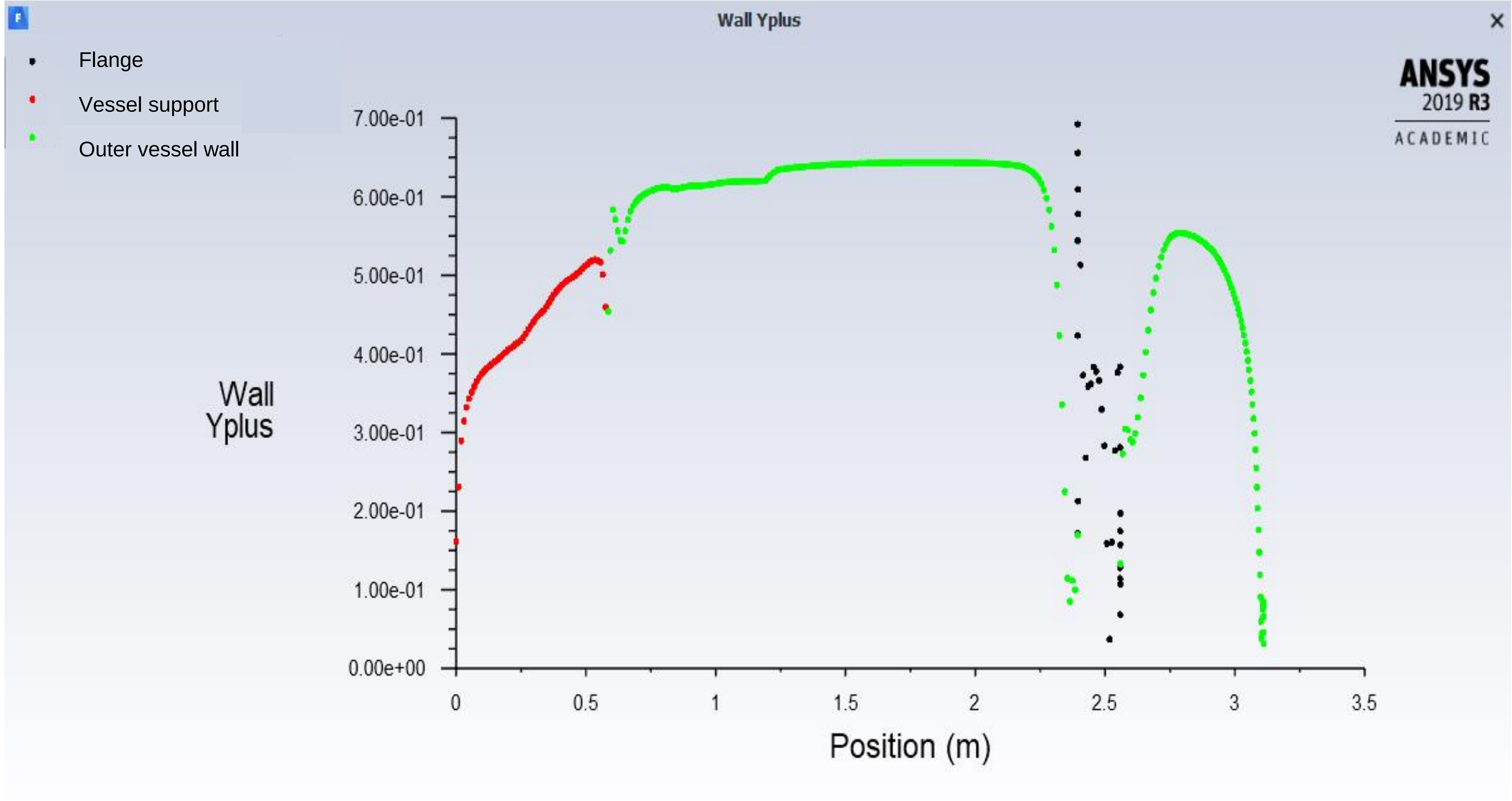


Source: Nuclear Power Technology Development Section, IAEA, Heat Transport and Afterheat Removal for Gas Cooled Reactors Under Accident Conditions, Vienna, 2000.

The temperature profile is comparable to profiles obtained by another researchers, published in the IAEA report


Pathlines Colored by Velocity Magnitude (m/s)
ANSYS
2020 R2
ACADEMIC
pathlines-1
Velocity Magnitude
6.97e-01
6.28e-01
5.58e-01
4.88e-01
4.18e-01
3.49e-01
2.79e-01
2.09e-01
1.39e-01
6.97e-02
0.00e+00
(m/s)

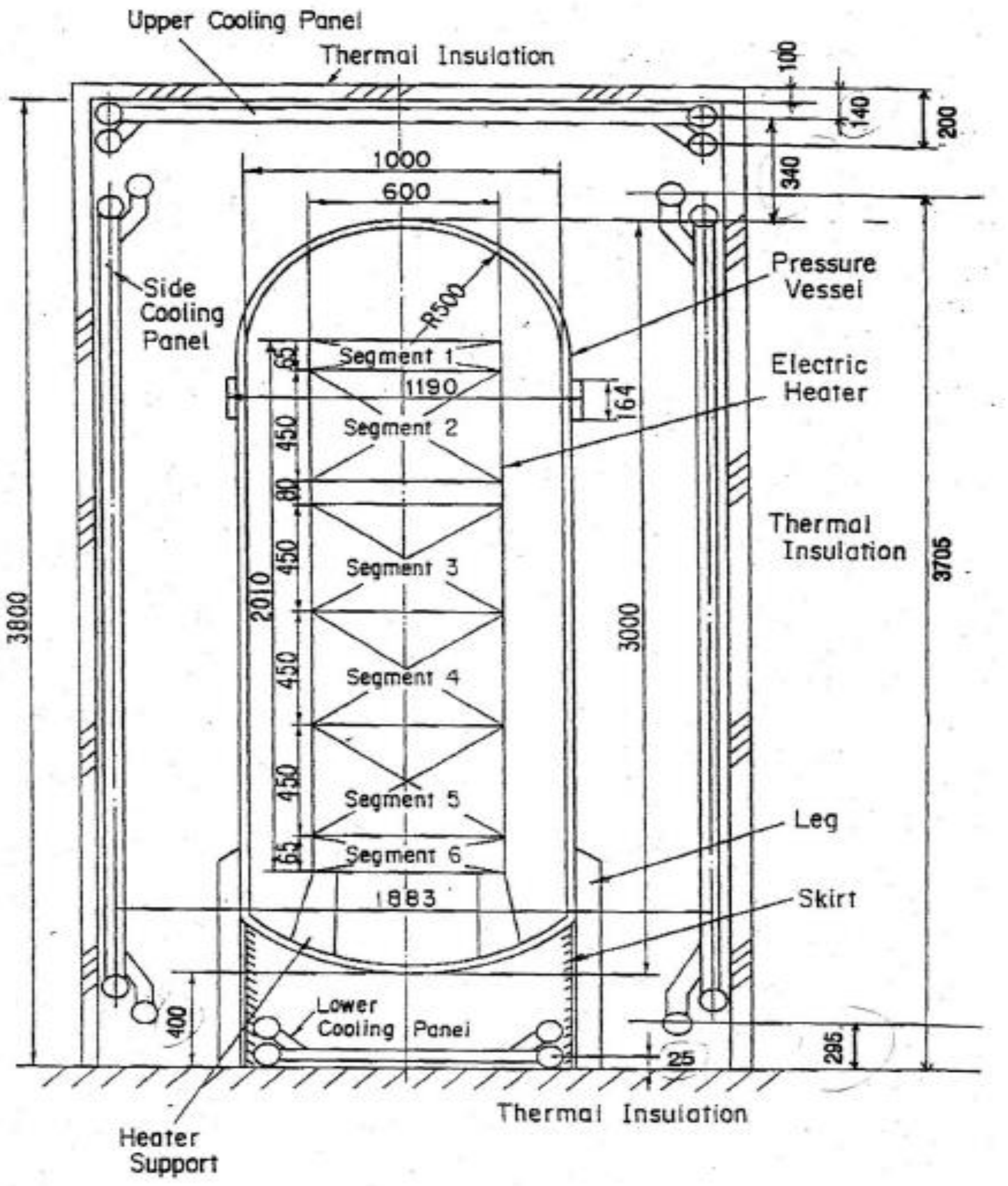
Contour plot of velocity in the vessel surroundings



Y+ value is close to 1 as required when using enhanced wall treatment

Experiment configuration No. 2

Configuration number		II
Gas inside the pressure vessel		He
Pressure [MPa]		0,73
Total heating power [kW]		28,79
Heating power of segments [kW]	No. 1	1,16
	No. 2	3,11
	No. 3	3,52
	No. 4	5,10
	No. 5	10,42
	No. 6	5,49
Cooling medium		Water



Ra ~ 3*10^7 => fluid flow inside the pressure vessel cannot be omitted; transitional flow

Method of „blackboxing” (simplifying) vessel surroundings

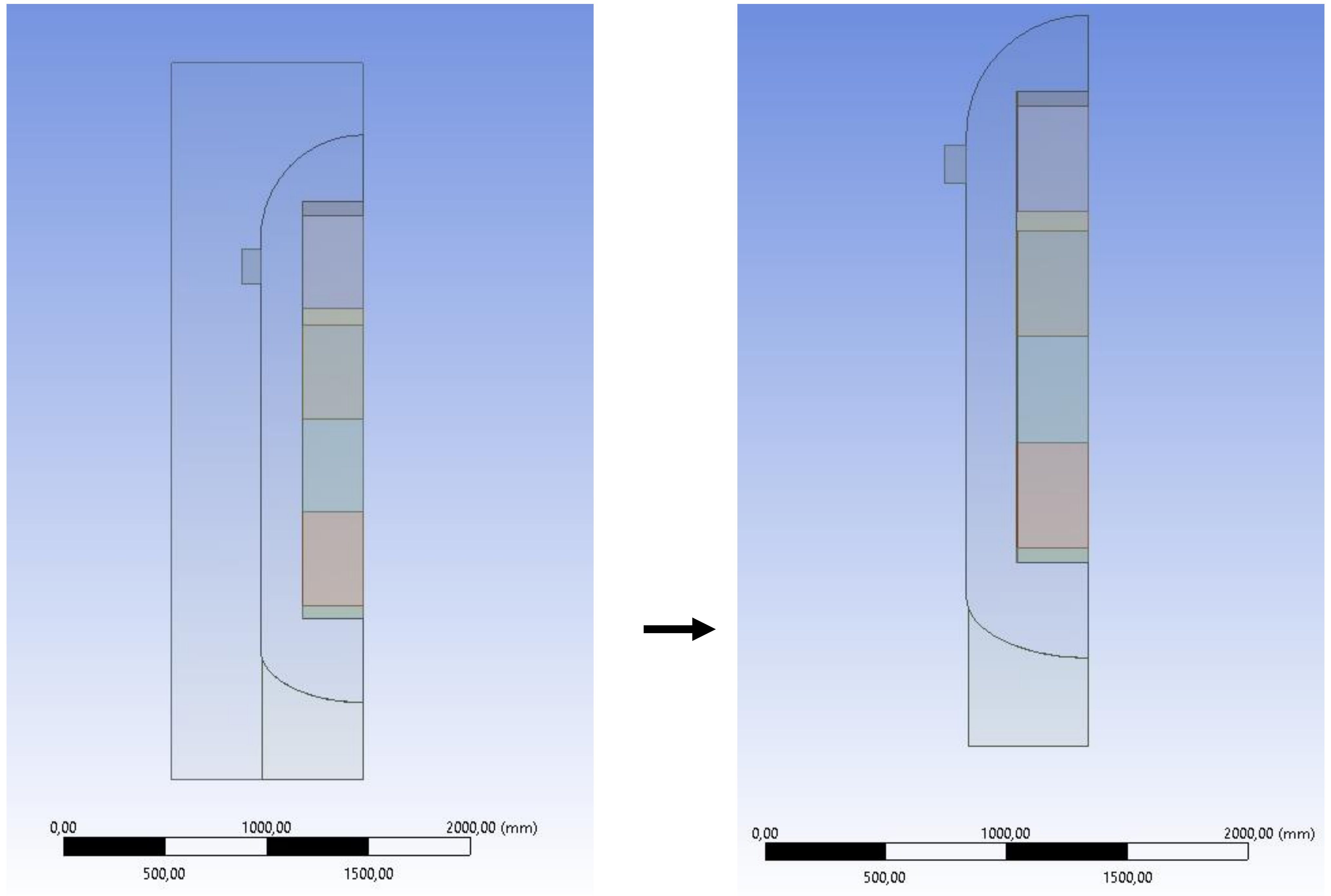
Problem – ANSYS educational license doesn’t allow for simulation of two fluids segregated by a barrier

Solution – replacing vessel surroundings with a convection-radiation boundary condition. The heat transfer coefficient and effective temperature of surroundings are updated after every iteration

Procedure:

1. Conducting simulations for immobile gas in the vessel interior (ANSYS educational allows for that) and mobile gas in vessel exterior with different heater powers
2. Saving the radiation and total heat flows and temperature profile along outer edge of the pressure vessel
3. Calculating heat transfer coefficient and effective temperature for radiation along the outer edge of the vessel

Coincidentally, the method decreases computational costs of simulation.

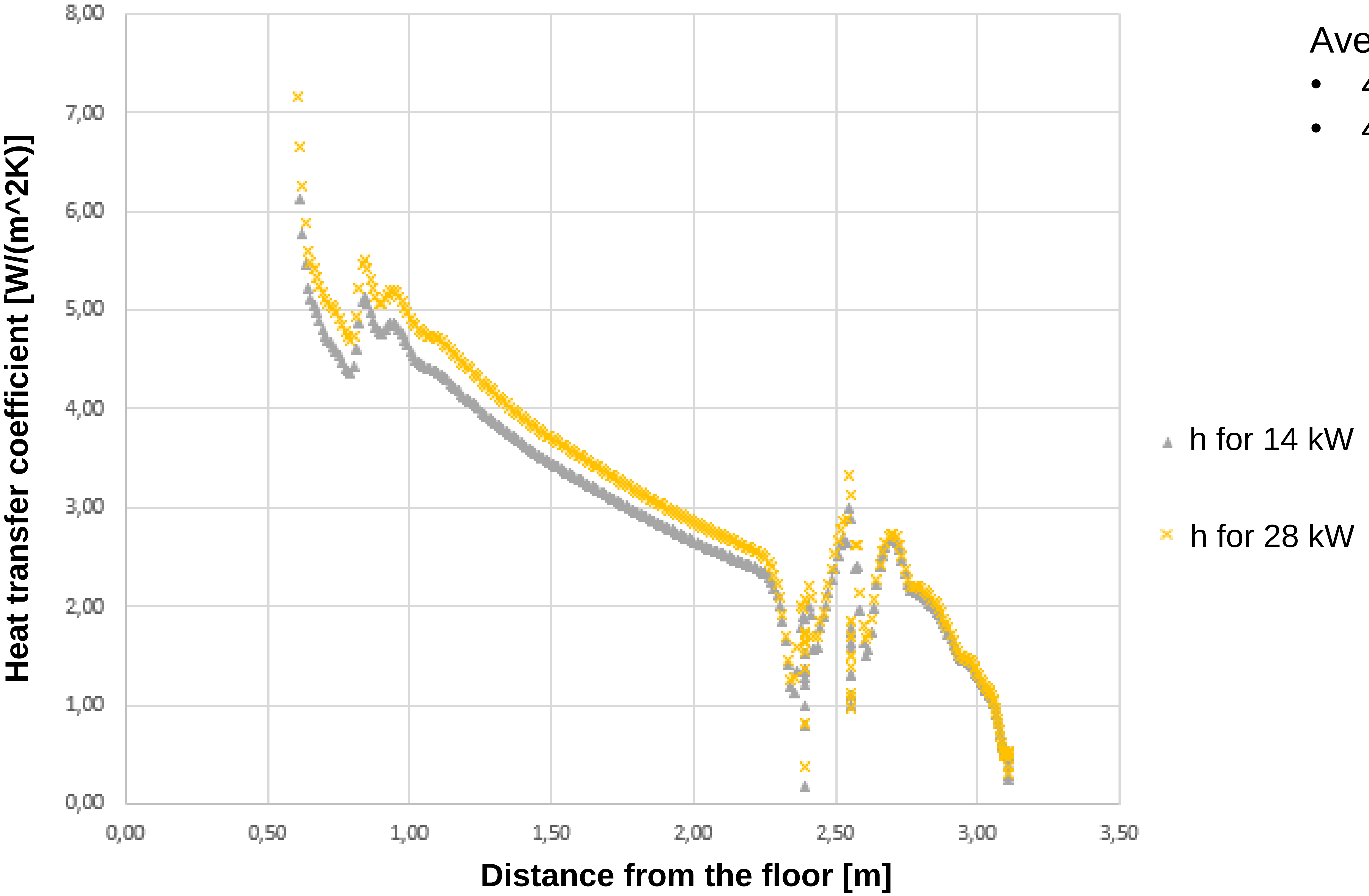


$$h = \frac{q_t - q_{rad}}{T_w - T_{ot}} \qquad T_{eff} = T_w - \frac{q_{rad}}{\varepsilon k}$$

h – heat transfer coefficient

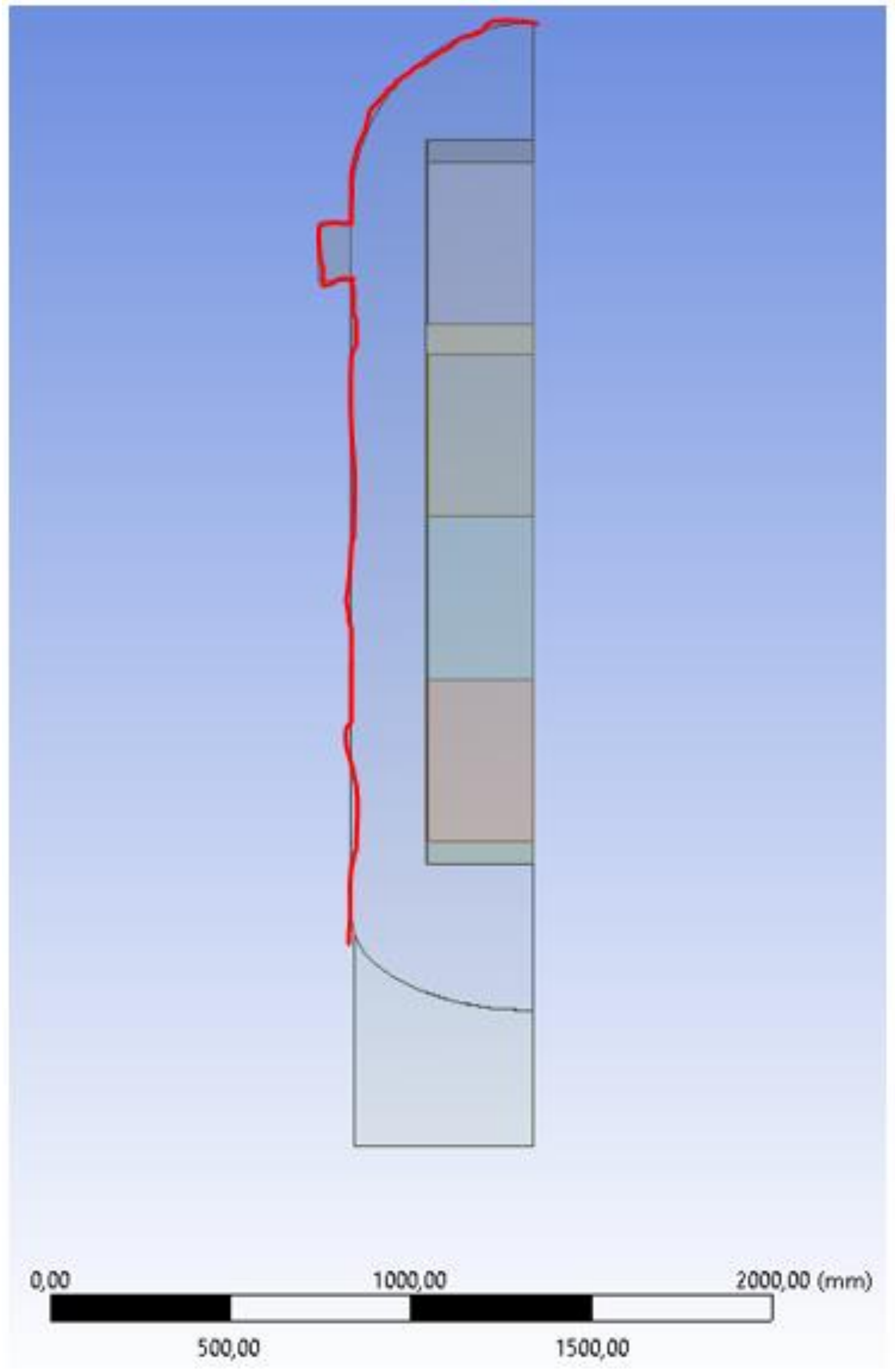
T_{eff} – effective temperature for radiation

Heat transfer coefficient along the edge of pressure vessel

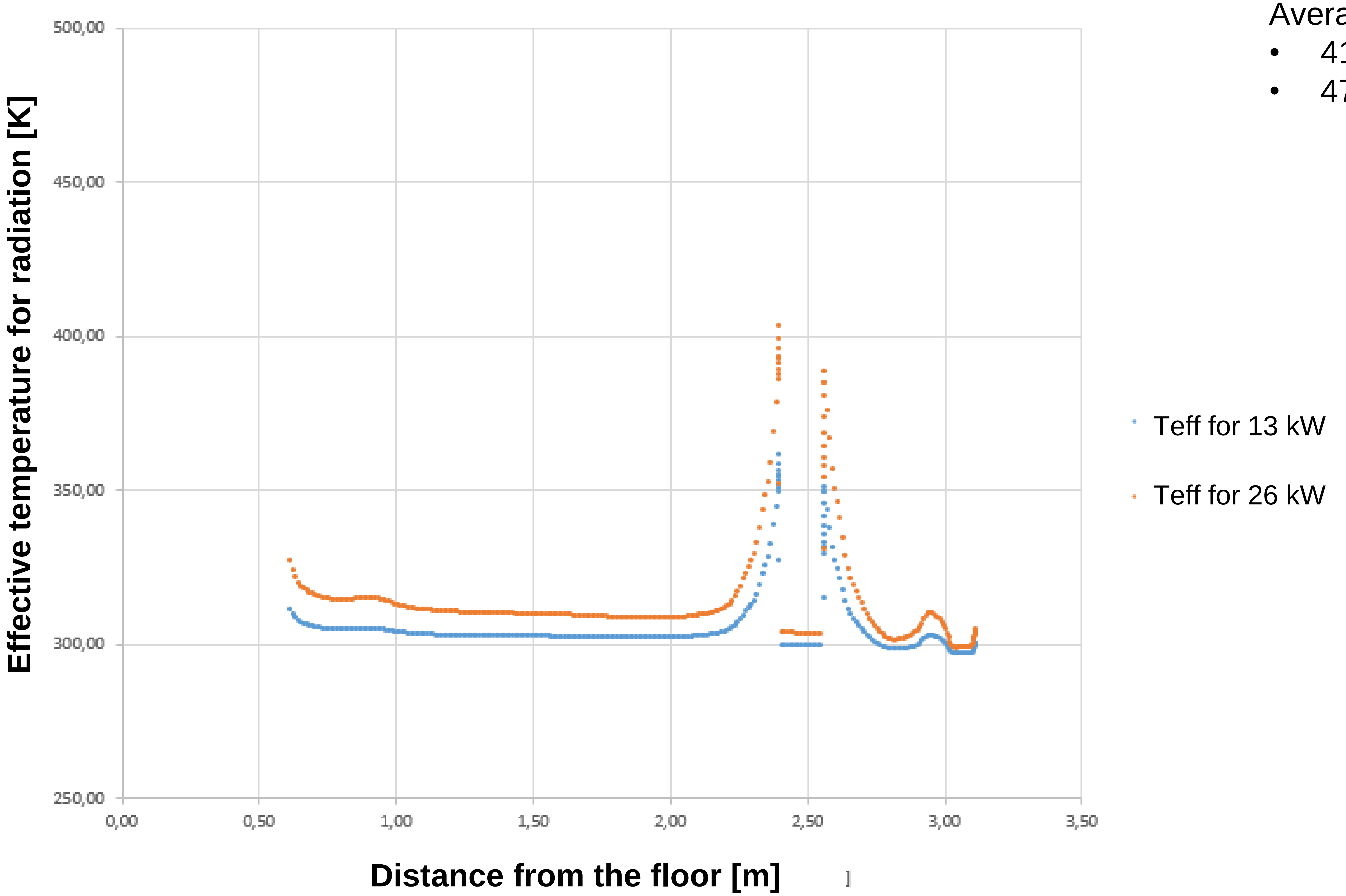


Average temperature of vessel outer edge

- 415 K for 13 kW
- 479 K for 26 kW

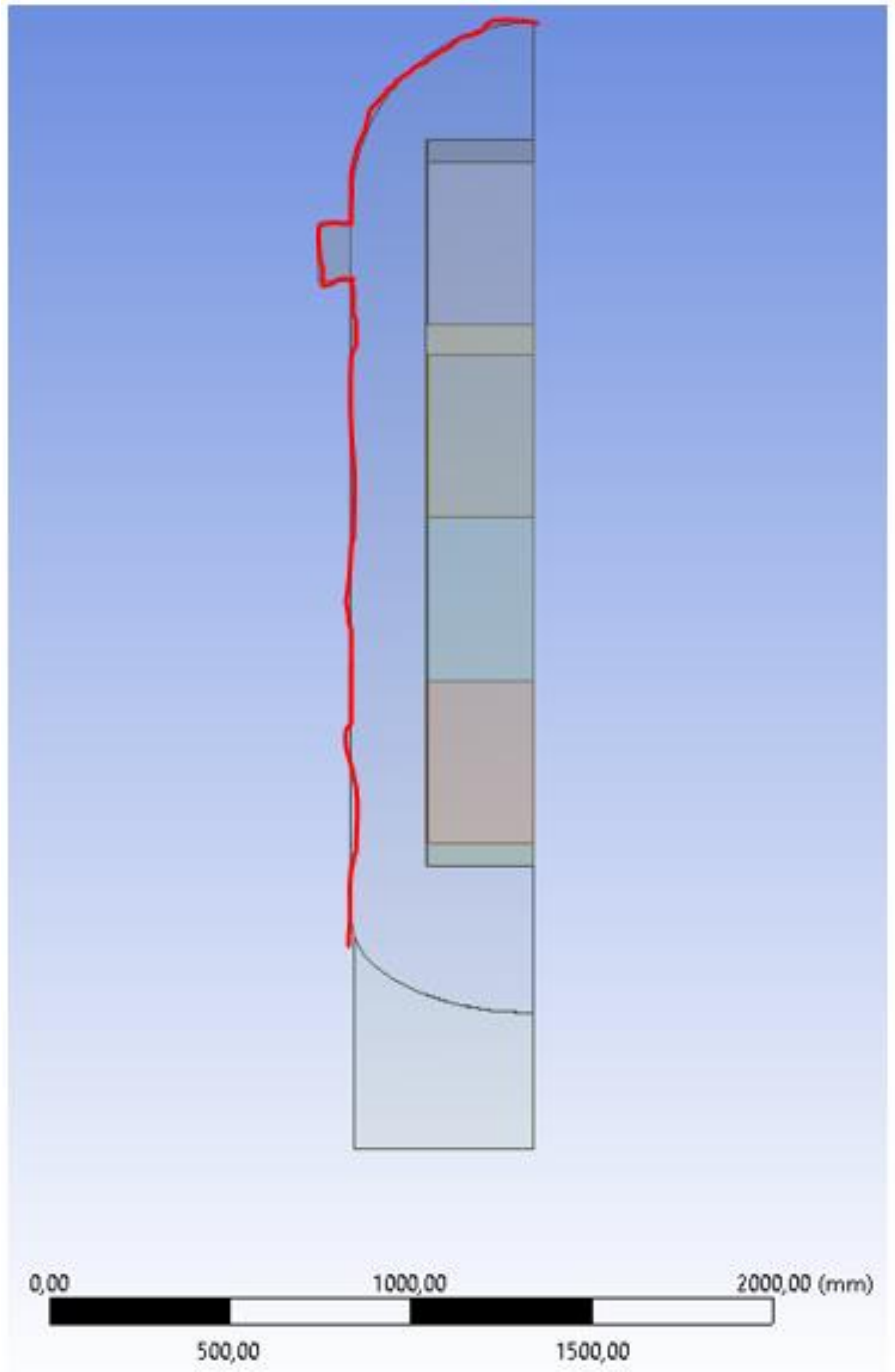


Effective temperature for radiation along the edge of pressure vessel



Average temperature of vessel outer edge

- 415 K for 13 kW
- 479 K for 26 kW



Correlations for heat transfer coefficients

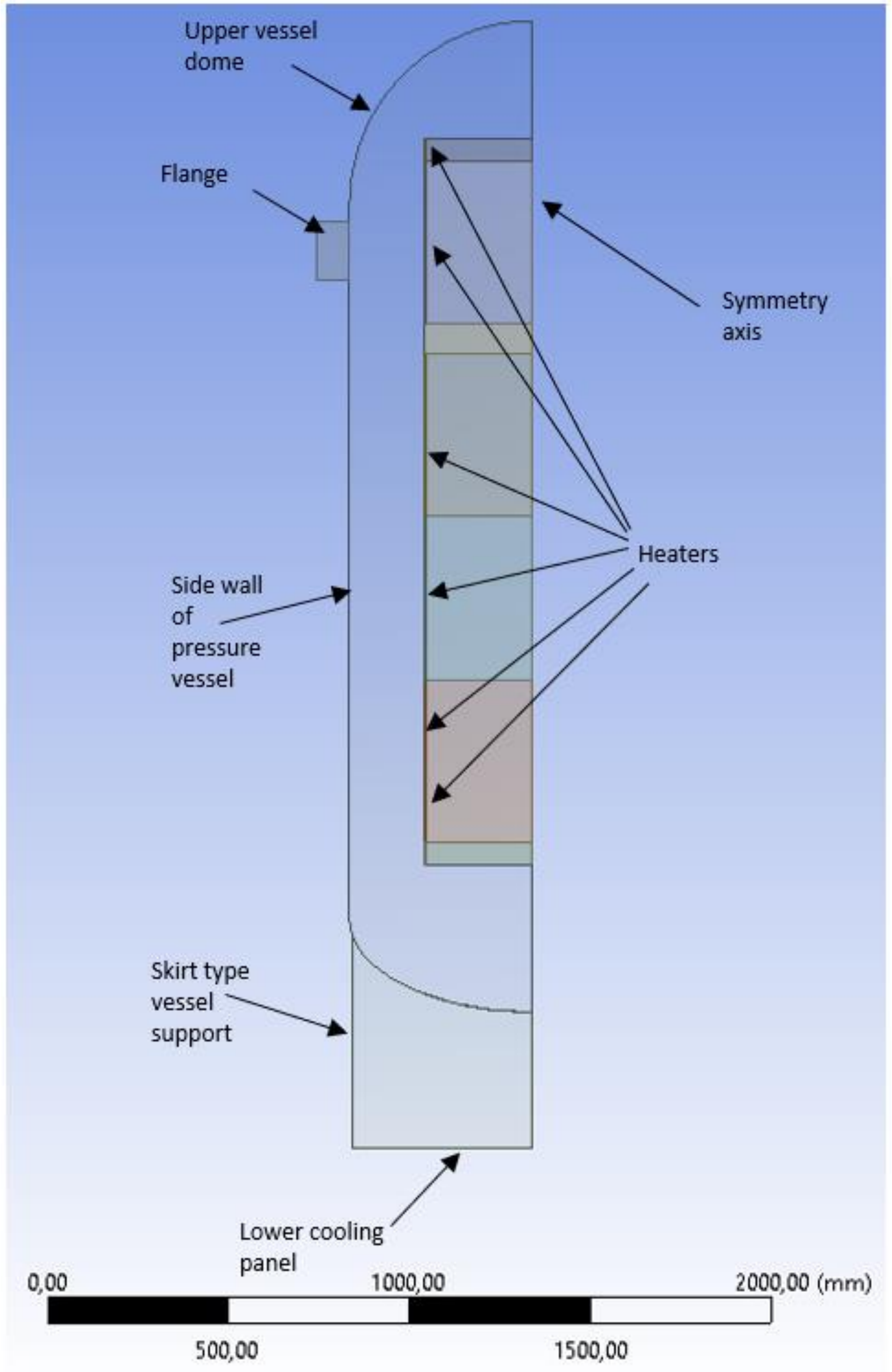
ΔT = Average temperature of vessel walls – average temperature of cooling panels

x = vertical coordinate of a particular finite volume edge

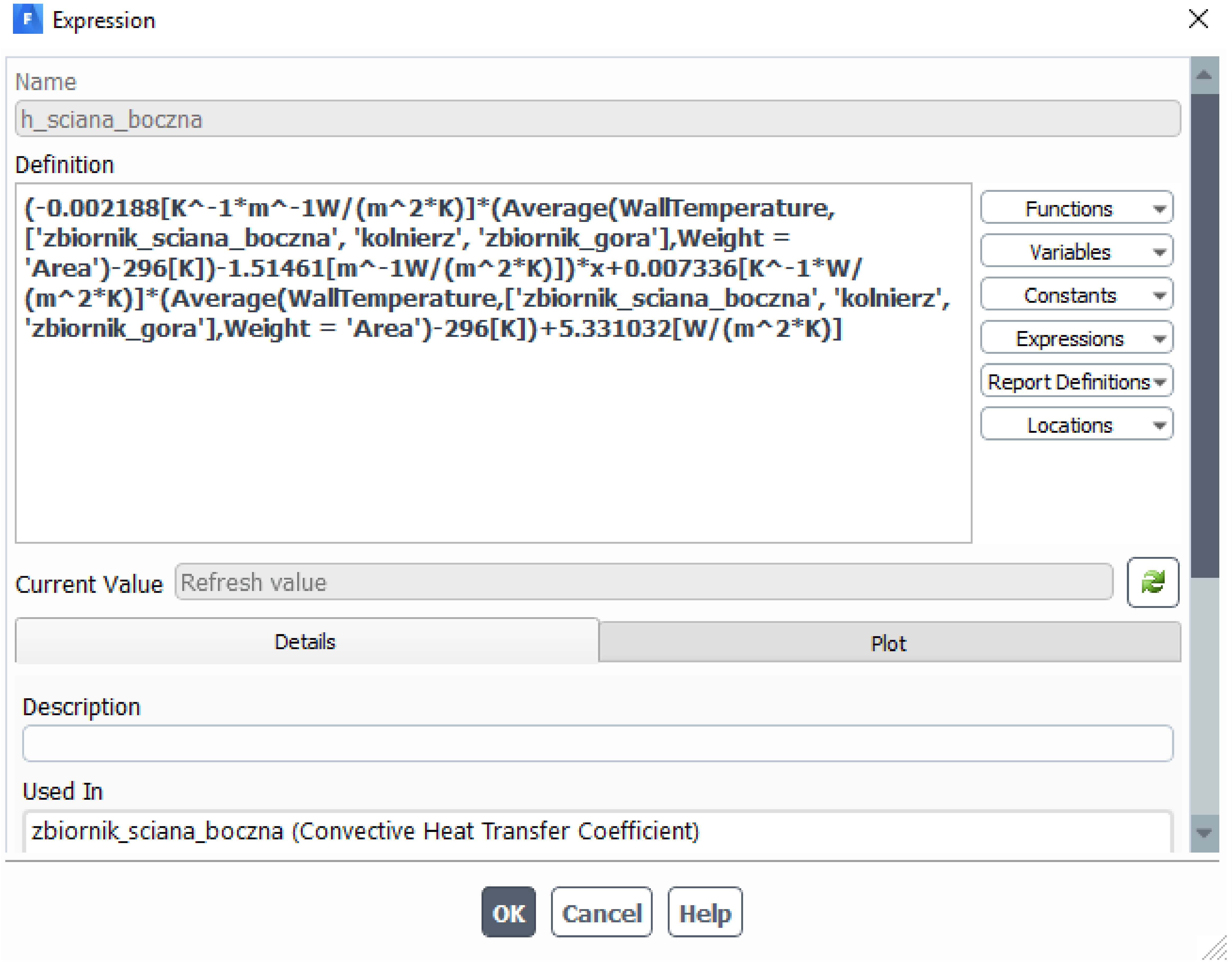
$$h = ax + b$$
$$a = a_1 \Delta T + b_1$$
$$b = a_2 \Delta T + b_2$$

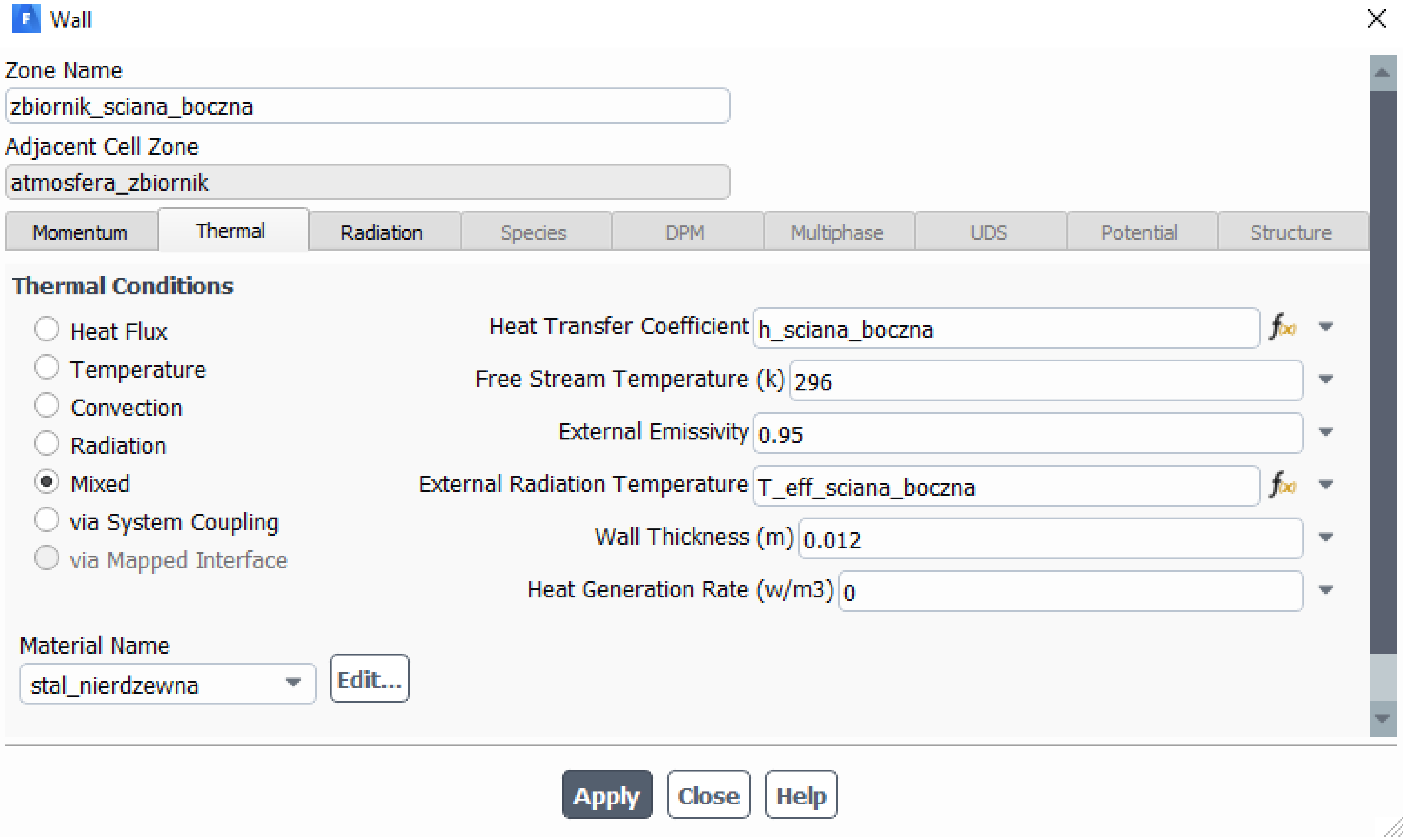
Geometry element	Correlations for heat transfer coefficient on edges of new calculational domain
Skirt type vessel support	17.0324996*x*x-6.5112997*x+0.006532ΔT+1.794666
Vessel side wall	(-0.002188ΔT-1.51461)*x+0.007336*ΔT +5.331032
Flange	2.1
Upper vessel dome	(-0.003219*ΔT-4.79179)*x+0.010041*ΔT+15.485625

Correlations for effective surrounding temperature for radiation look similar to the correlations above



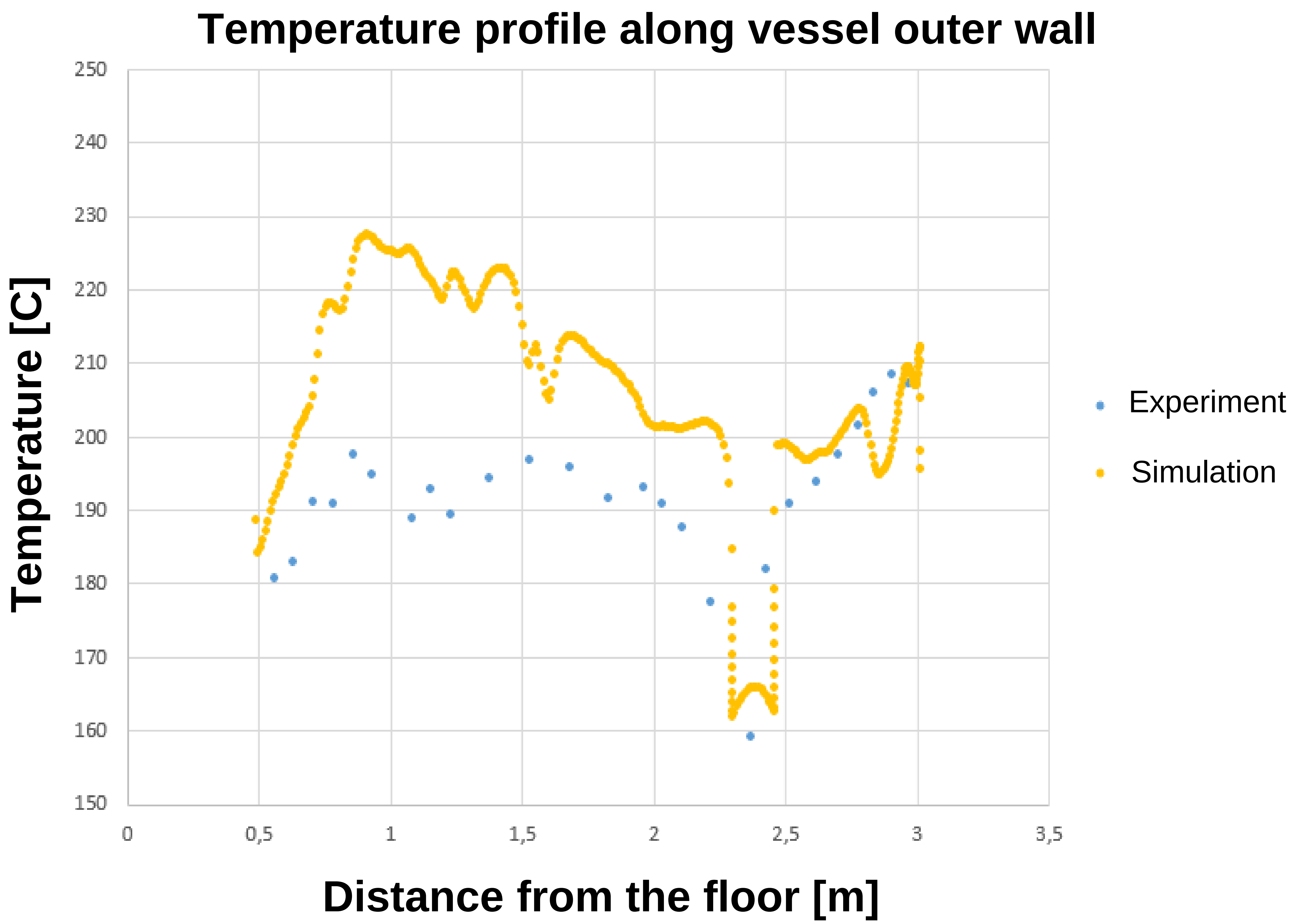
Implementation of heat transfer coefficients

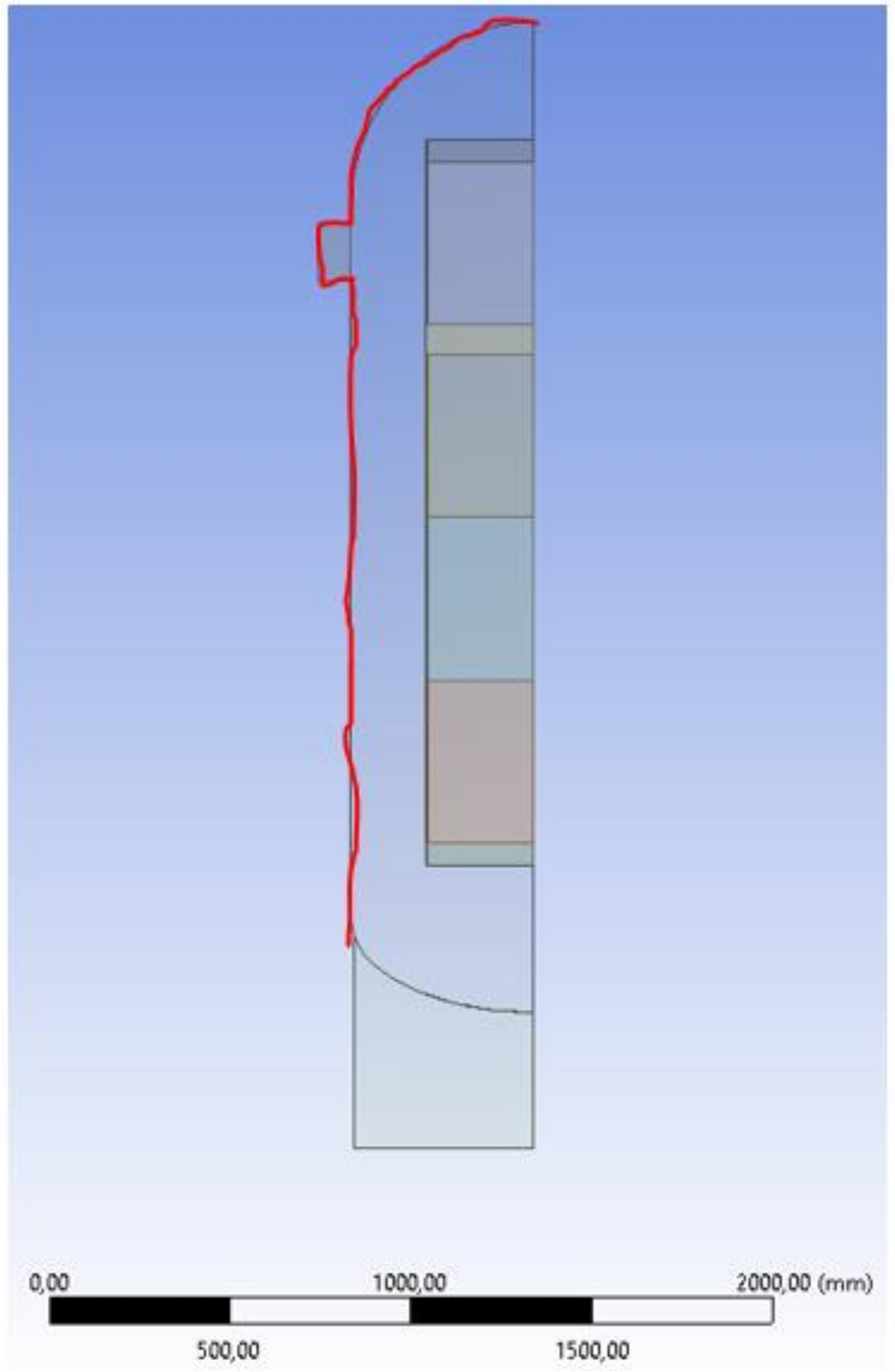




Simulation results for configuration No. 2

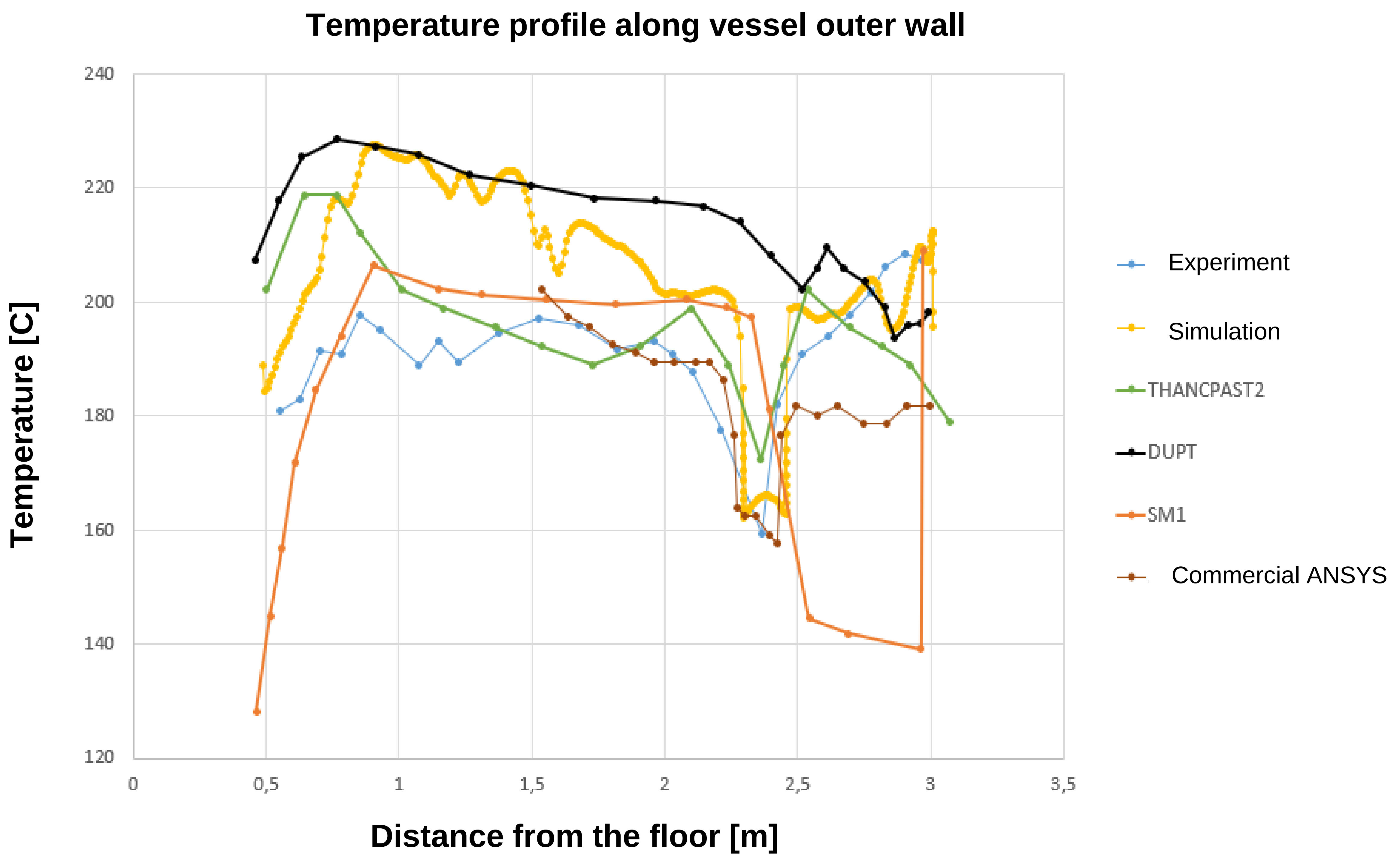
Configuration number		II
Gas inside the pressure vessel		He
Pressure [MPa]		0,73
Total heating power [kW]		28,79
Heating power of segments [kW]	No. 1	1,16
	No. 2	3,11
	No. 3	3,52
	No. 4	5,10
	No. 5	10,42
	No. 6	5,49
Cooling medium		Water





The agreement between simulation results and experiment is acceptable below the flange (up to 15 % difference) and good above the flange

Model geometry for configuration No. 2

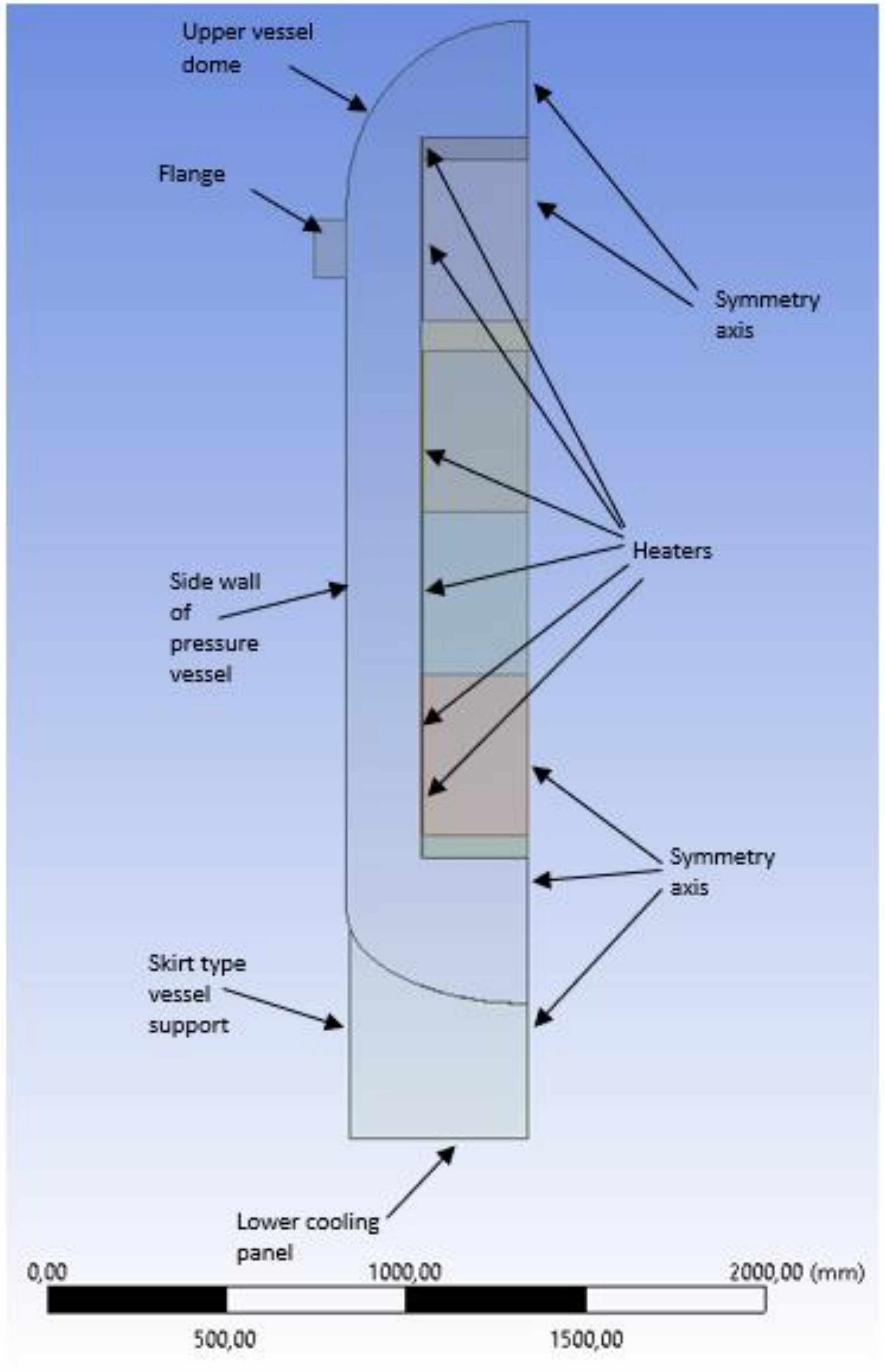


Source: Nuclear Power Technology Development Section, IAEA, Heat Transport and Afterheat Removal for Gas Cooled Reactors Under Accident Conditions, Vienna, 2000.

The temperature profiles obtained by other researchers look similar. The best fit was achieved by using researchers using commercial ANSYS

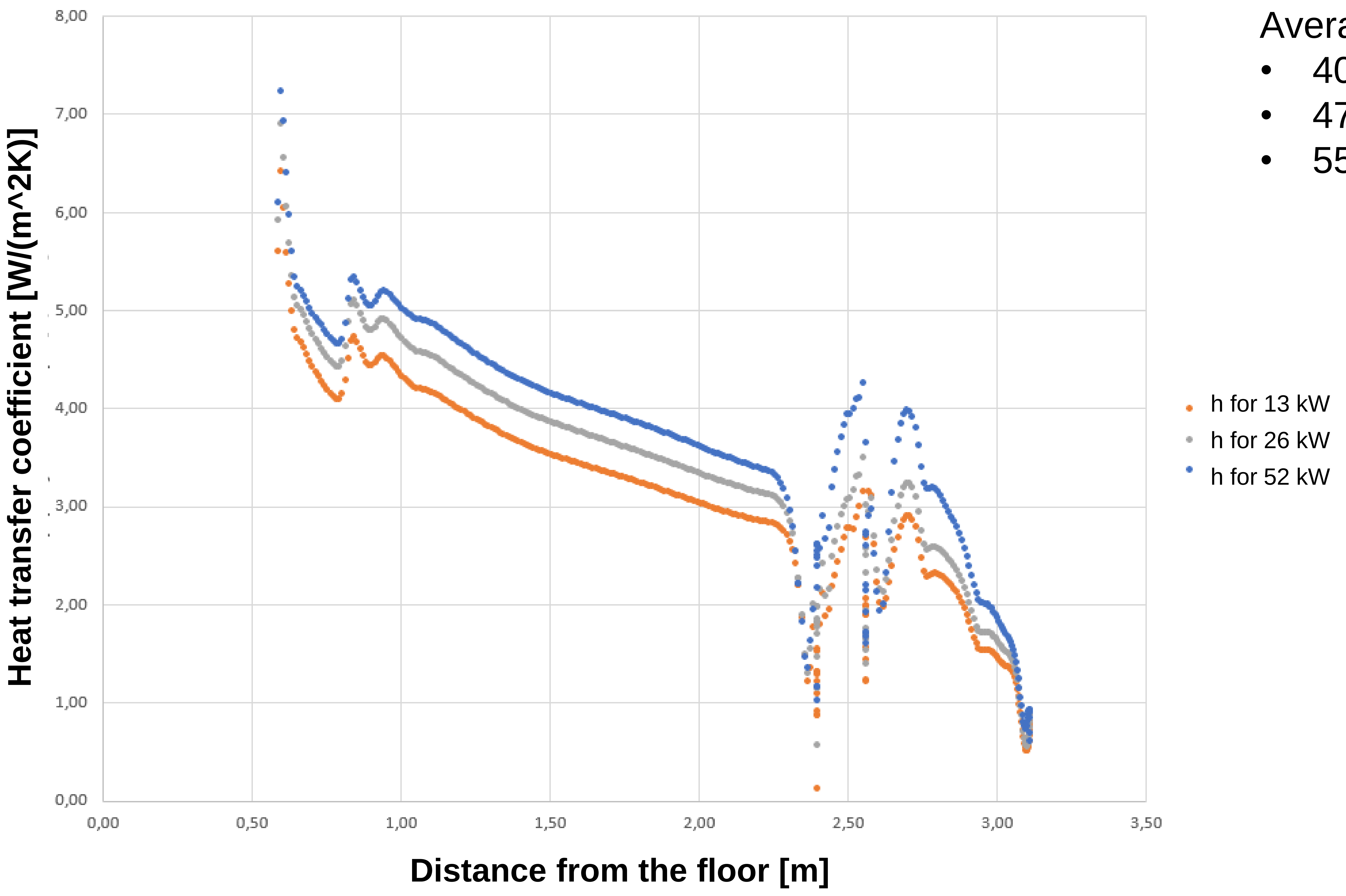
Model geometry for configuration No. 3

Configuration number		III
Gas inside the pressure vessel		N_2
Pressure [MPa]		1,1
Total heating power [kW]		93,93
Heating power of segments [kW]	No. 1	5,90
	No. 2	16,05
	No. 3	19,88
	No. 4	22,24
	No. 5	22,13
	No. 6	7,72
Cooling medium		Water



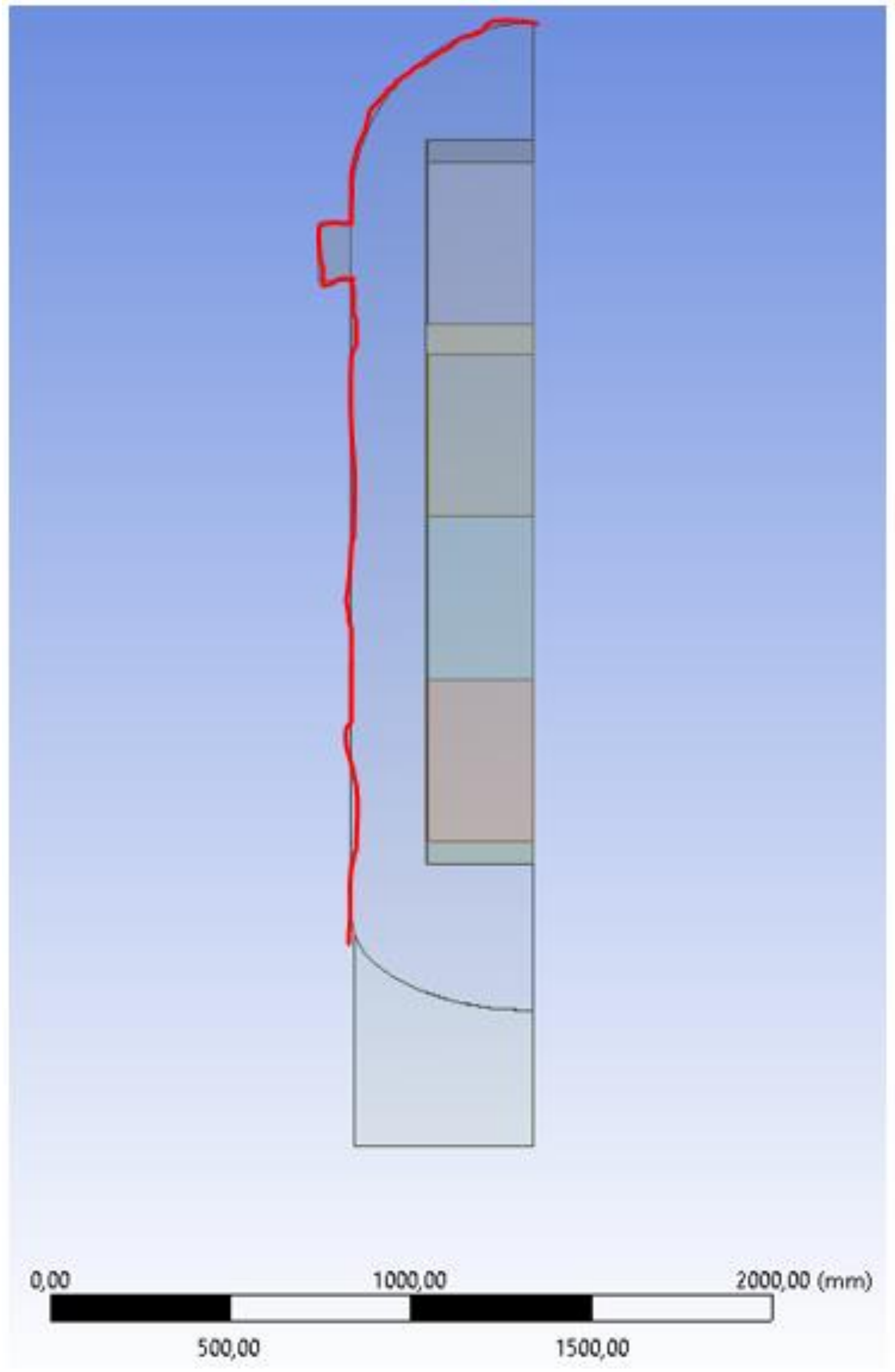
Ra ~ 4*10^8 => turbulent flow inside the vessel

Heat transfer coefficient along the edge of pressure vessel

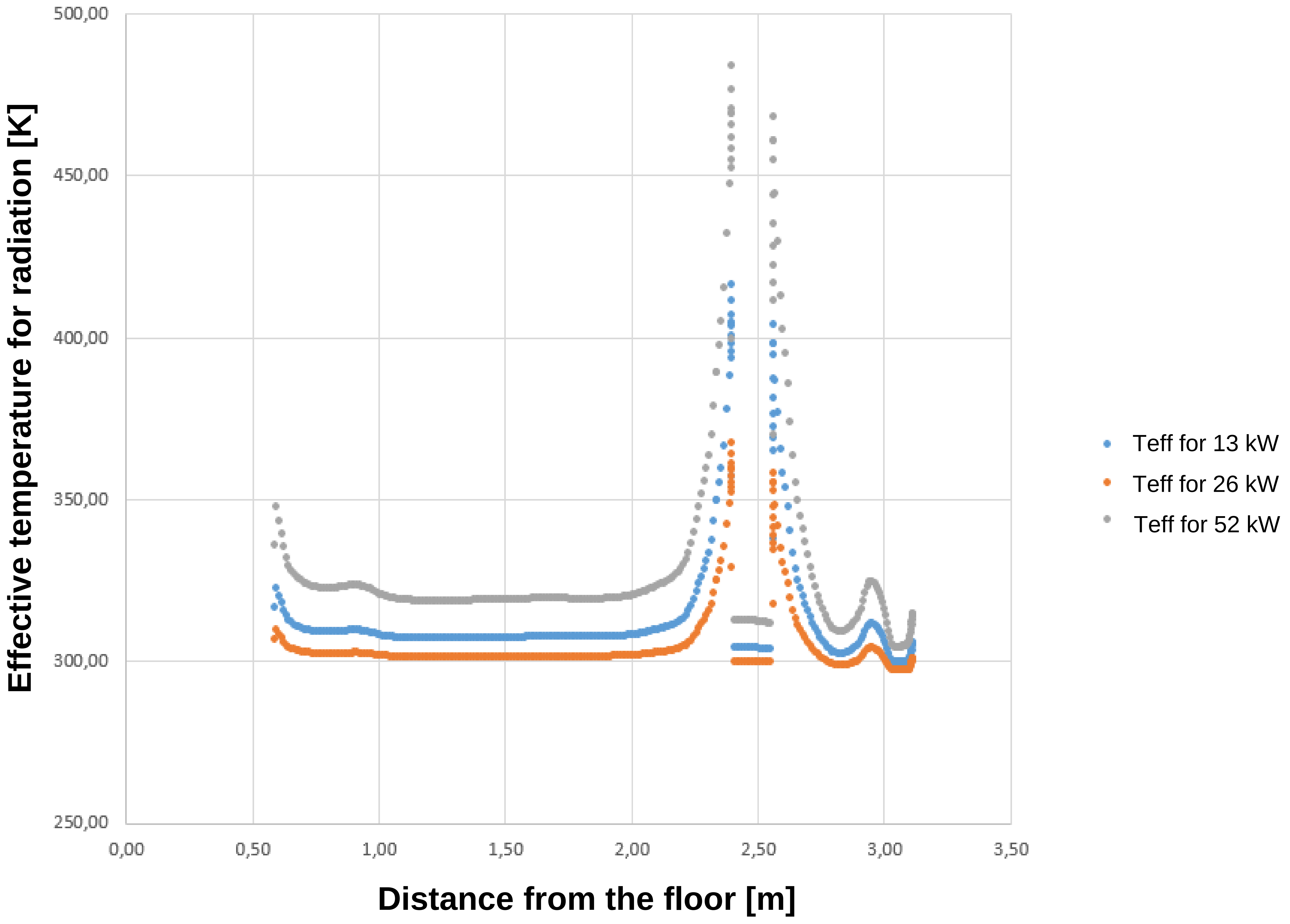


Average temperature of vessel outer edge

- 408 K for 13 kW
- 471 K for 26 kW
- 559 K for 52 kW



Effective temperature for radiation along the edge of pressure vessel



Average temperature of vessel outer edge

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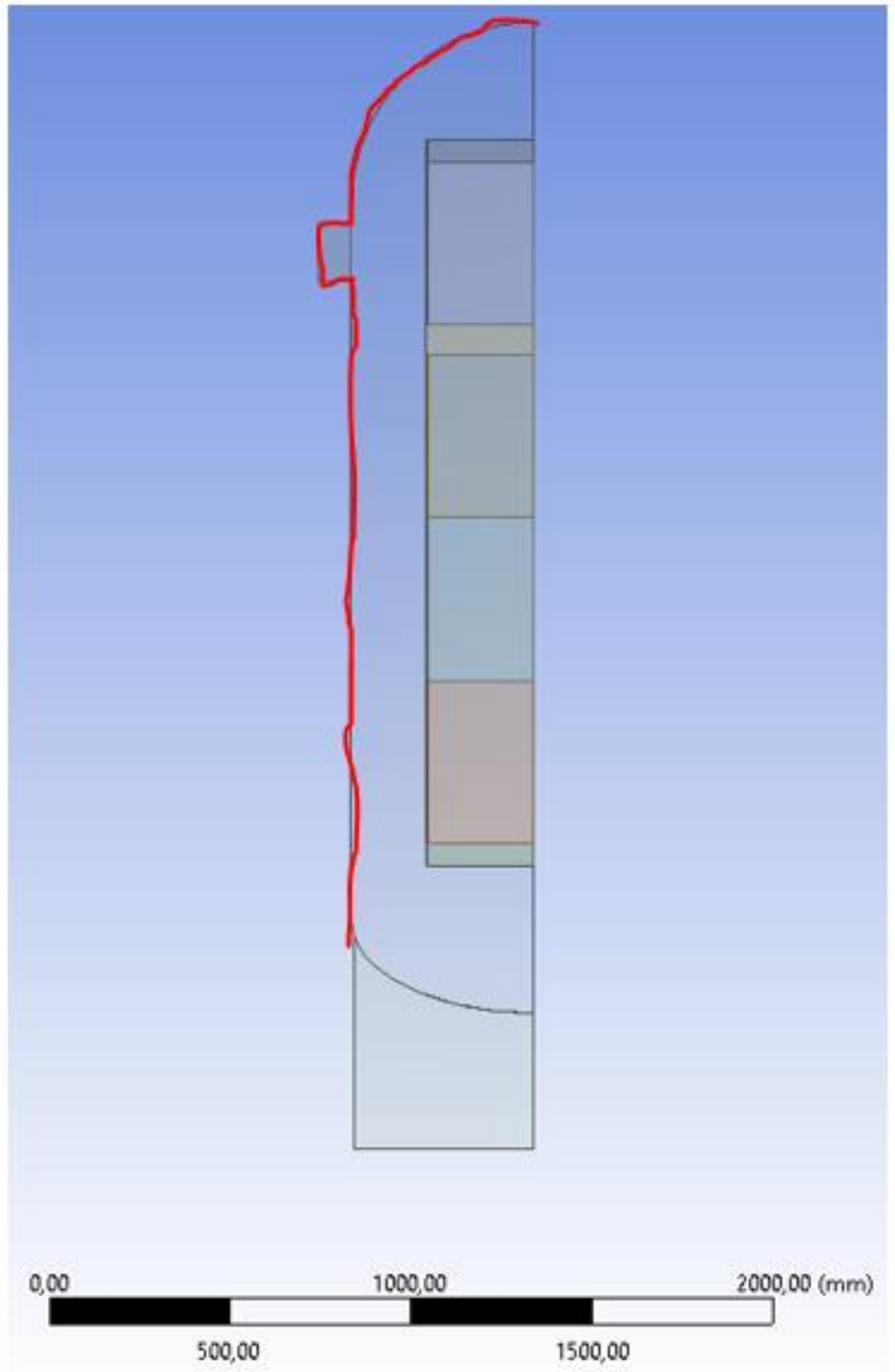
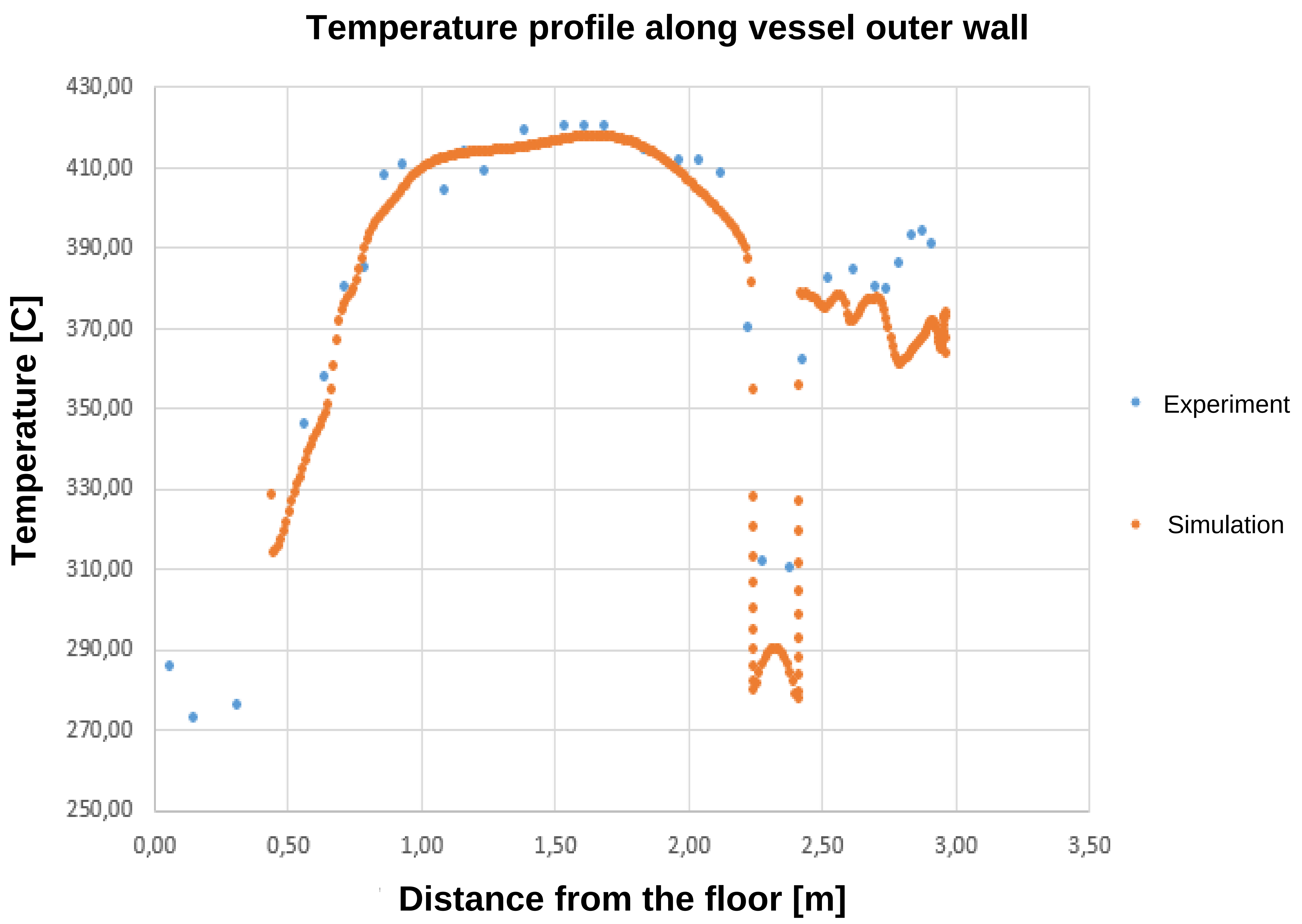
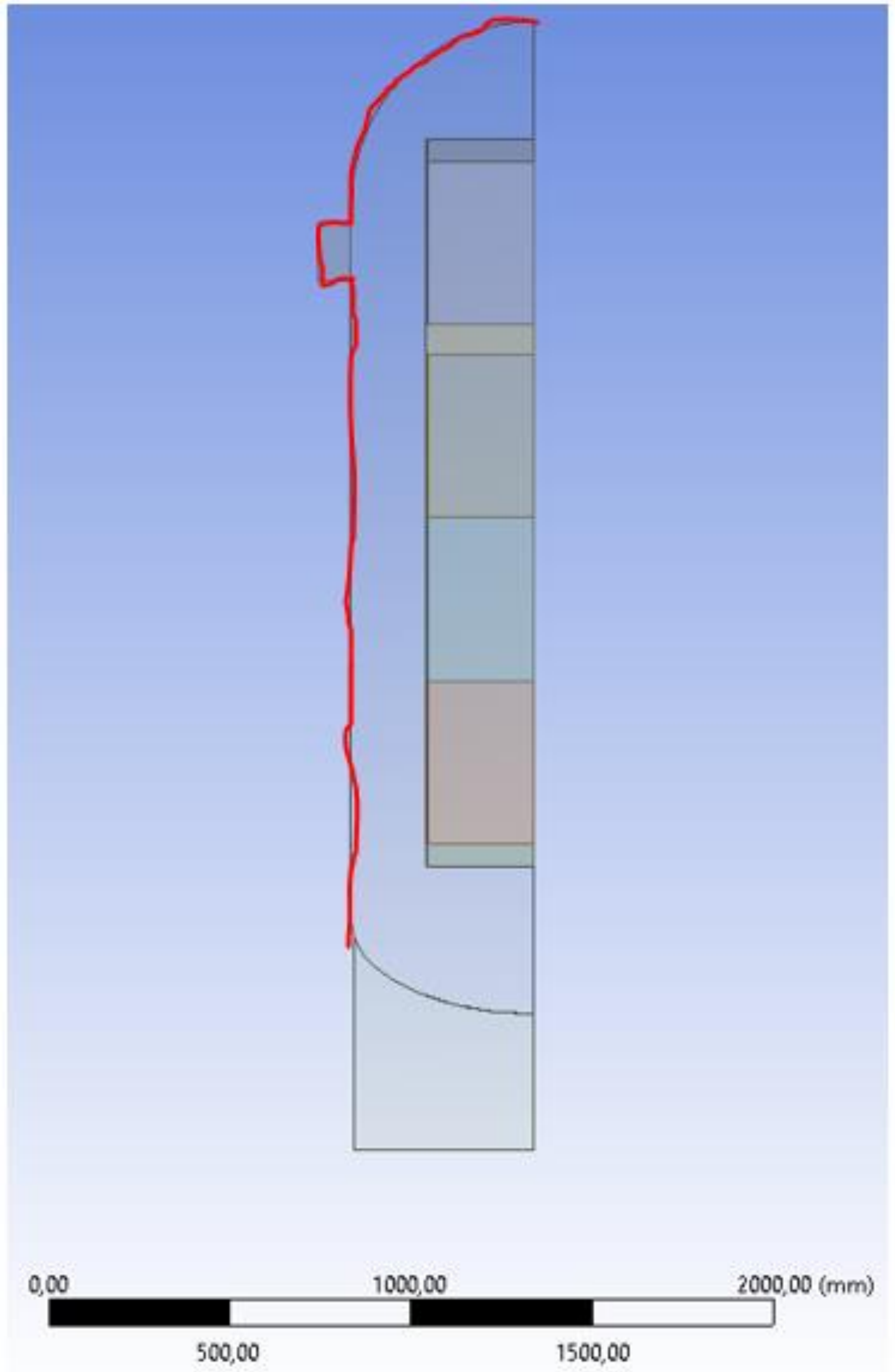
- 559 K for 52 kW



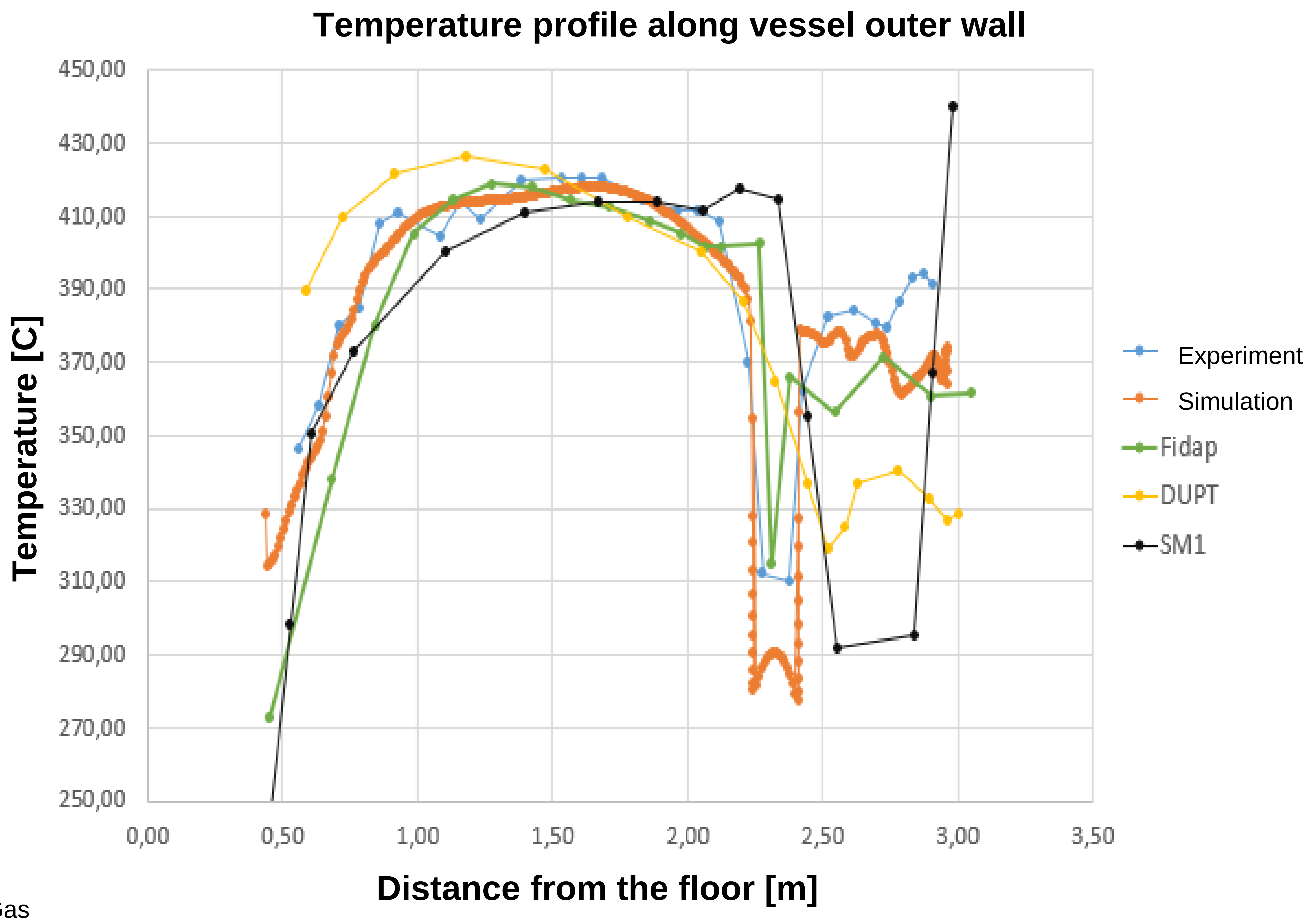
Results for configuration No. 3





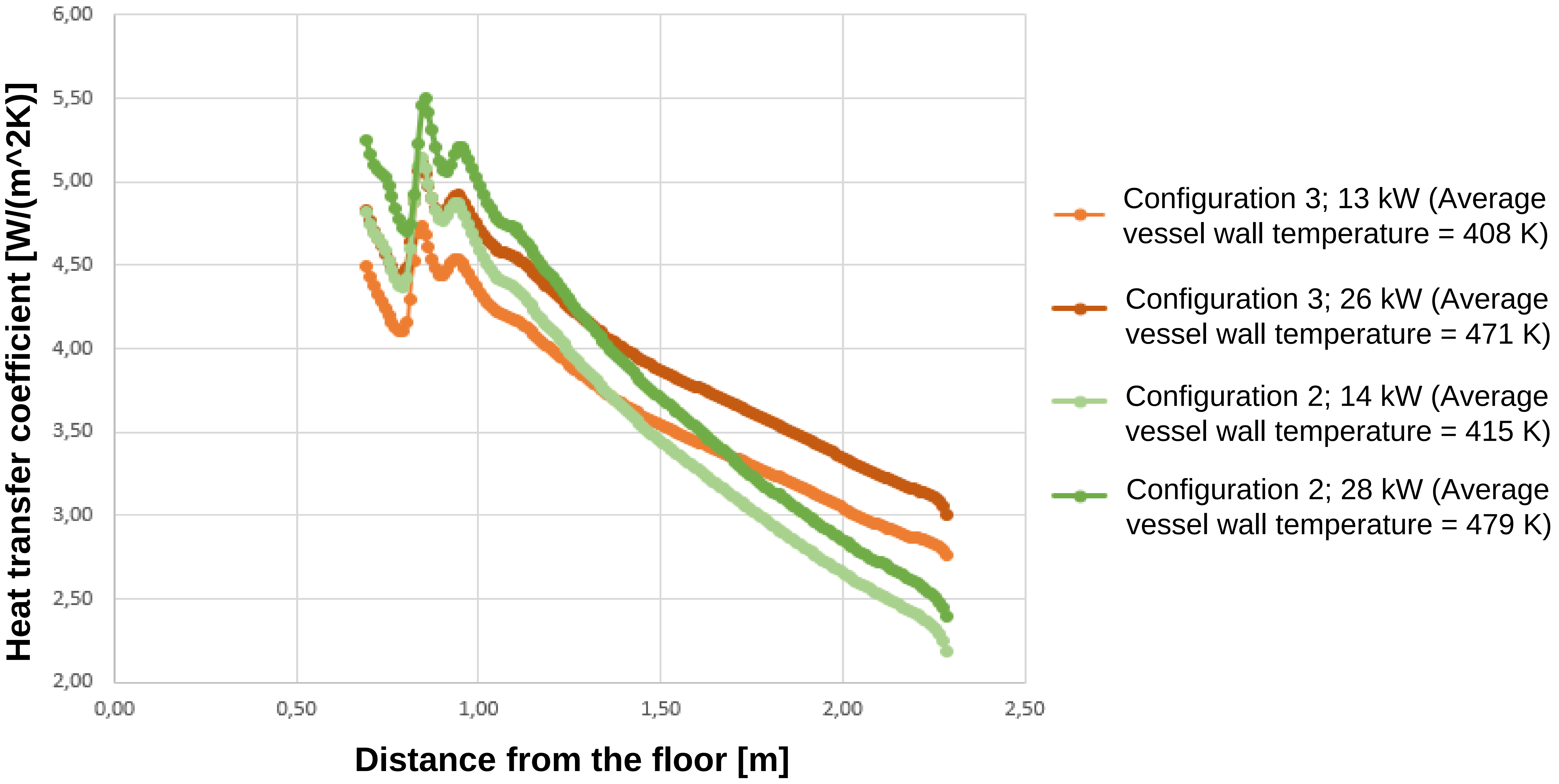
A nearly perfect agreement between simulation and experimental results was achieved

Comparison with results obtained by other researchers



Source: Nuclear Power Technology Development Section, IAEA, Heat Transport and Afterheat Removal for Gas Cooled Reactors Under Accident Conditions, Vienna, 2000.

Comparison of heat transfer coefficient profiles obtained when preparing correlations

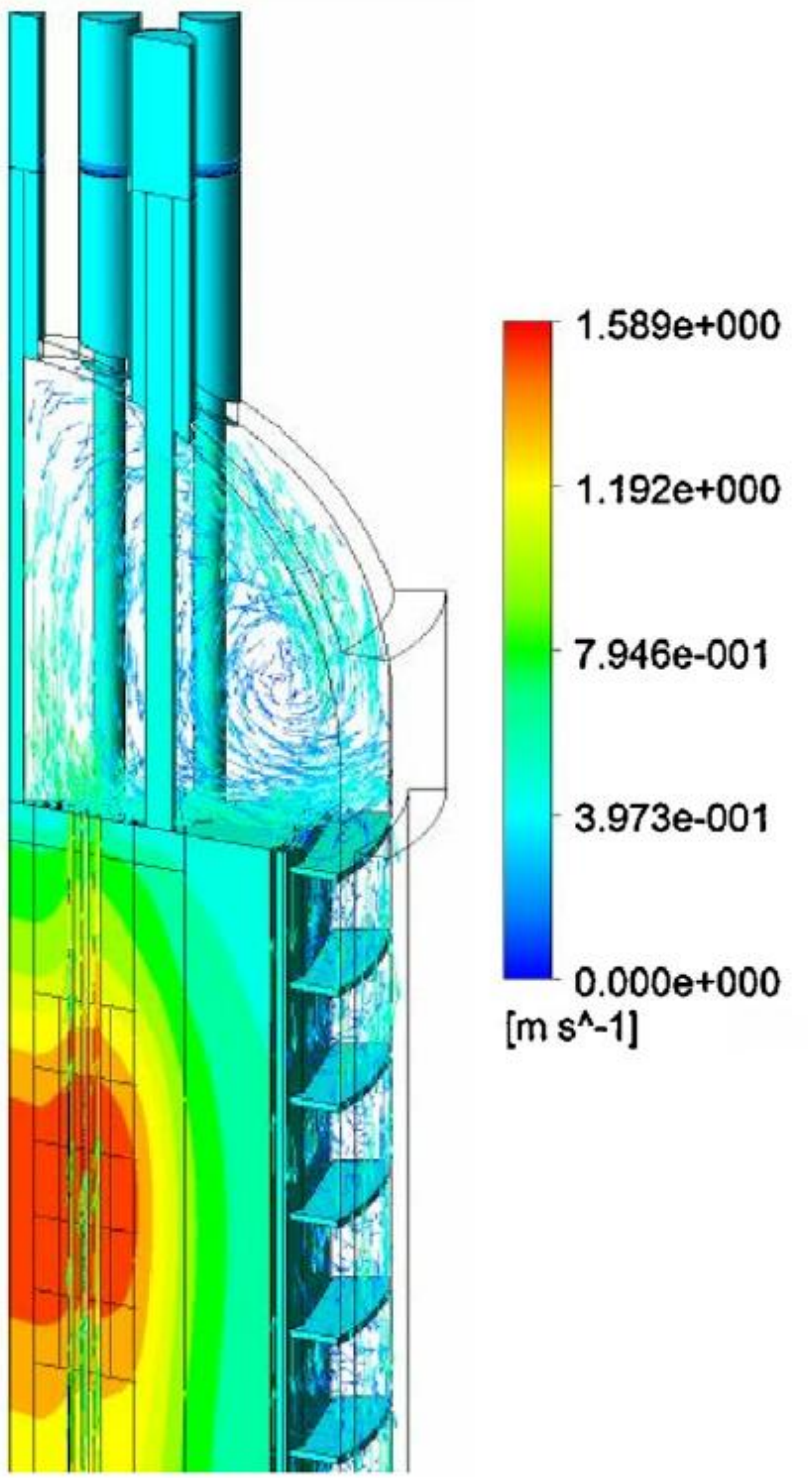


Heat transfer coefficient profiles slightly differ when heating power distributions are different

Strengths and weaknesses of the model

- \- Insufficiently good correlation describing boundary conditions. A more complex correlation is required, based on more or other inputs than average vessel temperature, surroundings temperature and finite volume coordinate
- \+ It is probably possible that the model could be used to simulate natural convection in other cases than enclosed systems
- \+ Using „blackboxing” method leads to a decrease in required calculational power
- \+ Eliminates the need to use literature-based heat transfer coefficients or allows to verify them

Possibilities of application of the developed calculational method



According to literature simulating fluid flow inside cooling channels leads to too large computational costs. Could blackboxing them lead to credible results?

An example of an attempt to apply CFD to calculation of HTTR reactor is visible on the left. Reduced number of simulated channels to cut calculational costs led to overestimation of fuel temperature.

Study of the applicability of CFD calculation for HTTR reactor

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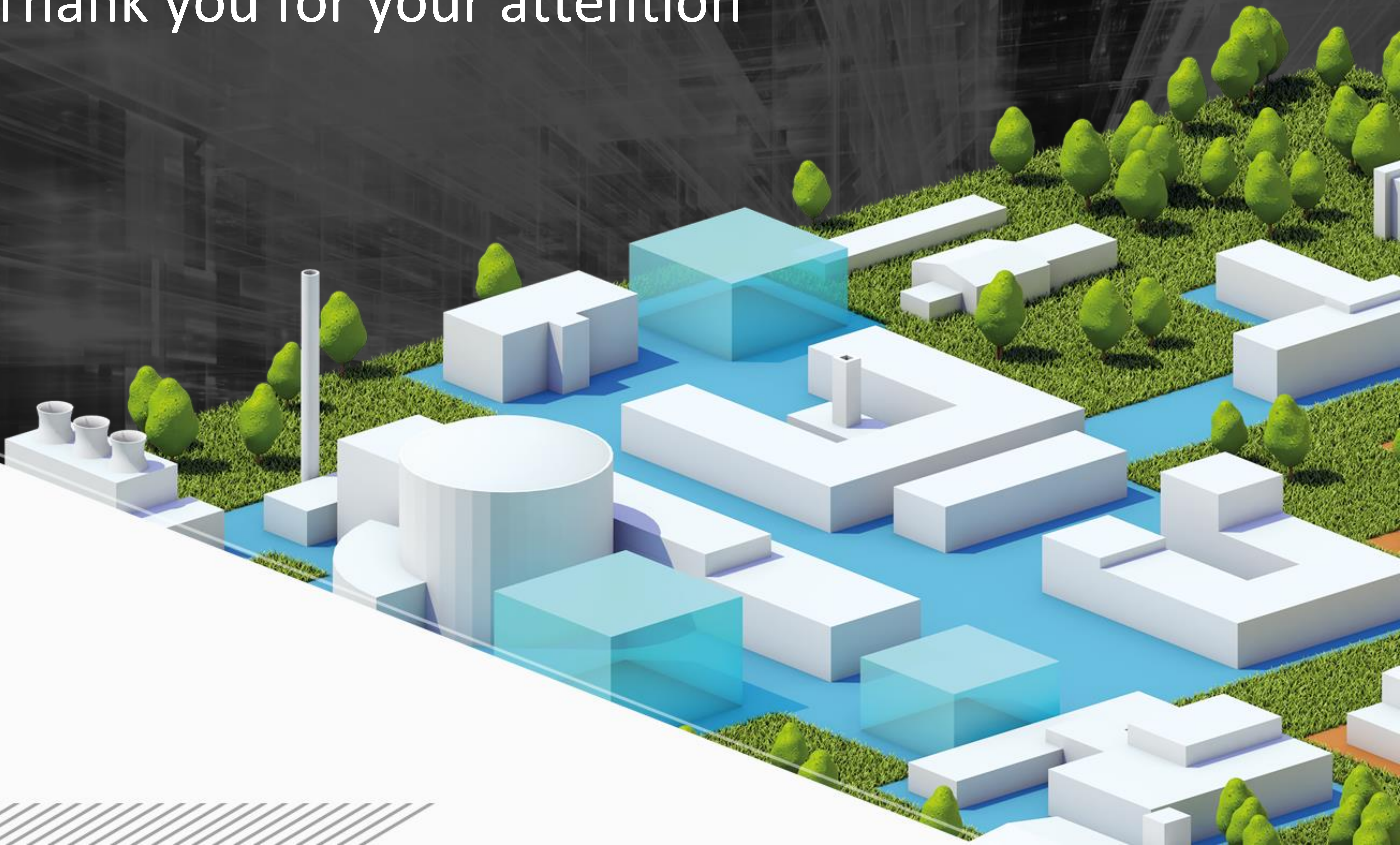
[b] Japan Atomic Energy Agency, Oarai-machi, Higashiibaraki-gun, Ibaraki-ken 311-1393, Japan

Thank you for your attention



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