

Calculating Temperatures Under Hood of a Prebake Anode Cell

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Plan of the Presentation

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- **Temperature under the hood sub-model:**
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 - Calculating the wt % H₂O in the air
 - Calculating the cell's evolution of CO and CO₂ and the air drawn into cell
 - Calculating Tblend
 - Calculating Qcombust and Qairburn
 - Calculating Cp(blend) used to calculate the temperature rise of Qtop, Qcombust and Qairburn
 - Calculating Cp(mix) used to calculate ΔT rise caused by removing heat from the anode rods
 - Calculating Tmix, Texh and Tairin
- **Analysis of results and applications**
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Introduction

A lump parameters+ model has been expanded by adding to it a new algebraic sub-model that calculates the temperature under the anode hood (Tairin). The new sub-model adds to the four algebraic sub-models presented at the TMS 2003. Again, this work is a follow up on the early cell modeling efforts started in the late 1950's.

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HEAT BALANCE AND
C.E. COMPUTATION

7 0 FH=0.74+ 0.065*Z2
8 0 QA=(0.025*(AH-3.)+0.034*ELI+0.
8 1 15*Z1)*AN*FT*FH
9 0 QAS=0.0535*AAS*FT*FH
10 0 QC=(0.70/R+0.25/(R*B*B))* (1.+0
10 1 .09*ELI)*AC*FT*FH
11 0 QCO=(0.04*TB-26.0)*TO*AO/1440.
12 0 QB=(TB-TR)/(1897.0*RB)
13 0 QCB=0.0425*ACB*FT
```

Anode panel heat loss sub-model

DYNA/MARC: Advance Anode Panel Heat Loss

Advance Anode Panel heat Loss

Anode Stud Diameter	0.18	m
Number of Stud(s) per Anode	3	
Average Thickness of Cast Iron around Studs	0.02	m
Stud Hole Depth	0.14	m
Average Carbon Thickness under the Stud at Mid Anode Life	0.24	m
Thermal Conductivity of the Anode Carbon	4	W/m °C
Average Thickness of Cover Material Above Anode	0.16	m
Thermal Conductivity of Cover Material at Low Temperature	0.4	W/m °C
Thermal Conductivity of Cover Material at High Temperature	2	W/m °C
Temperature of the Cover Material Thermal Conductivity Transition	770	°C
Average Temperature of the Air Under the Hood	175	°C
Reference Anode Panel Studs Yokes and Rods Heat Loss	132.268976	KW

Activate Deactivate

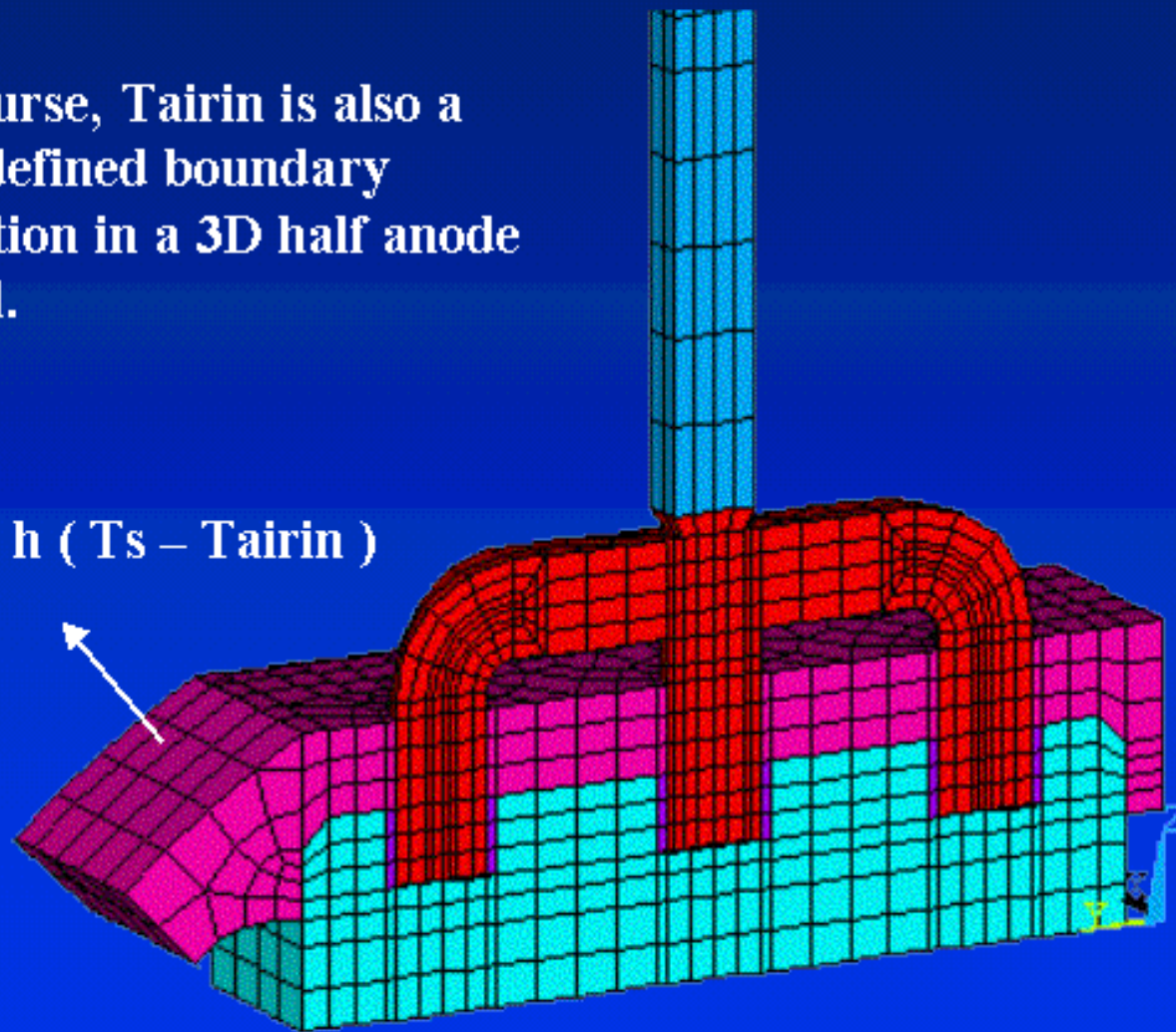
As seen before, the anode panel heat loss sub-model requires the user to specify the average air temperature under the hood (T_{airin}).

$$\begin{aligned}
 Q_{stud} (kW) &= 1 \cdot (k_{stud} / R_{stud} + R_{air} / 25) \\
 R_{stud} (m) &= 2 \cdot \ln(20000 / (4 \cdot \pi \cdot D_{stud} \cdot L_{stud} \cdot k_{stud})) \\
 R_{air} (m) &= L_{stud} \cdot W_{stud} \cdot k_{air} \cdot R_{air} \\
 R_{air} (m) &= L_{stud} \cdot W_{stud} \cdot R_{air} \cdot R_{air} \\
 R_{stud} (m) &= 2 \cdot \ln(20000 \cdot (D_{stud} + 2 \cdot T_{stud}) / R_{stud}) \\
 Q_{stud} (kW) &= 400 \cdot W_{stud} \cdot (k_{stud} \cdot R_{stud} \cdot R_{stud} \cdot 10) \\
 T_{stud} (°C) &= 0.0015 \cdot Q_{stud} - 0.00004 \cdot (Q_{stud})^2 \\
 R_{air} (m) &= L_{stud} \cdot W_{stud} \cdot k_{air} \\
 T_{air} (°C) &= (T_{stud} - T_{air}) \cdot R_{air} \cdot (k_{stud} \cdot R_{stud} \cdot R_{stud}) \\
 T_{air} (kW) &= (Q_{stud} - R_{air} \cdot T_{air}) \cdot (1.4185555 \cdot k_{air} \cdot L_{stud} \cdot W_{stud} \cdot R_{air} \cdot 10) \\
 &= 1.8 \cdot k_{air} \cdot L_{stud} \cdot W_{stud} \\
 Q_{stud} (kW) &= (Q_{stud} - 1.8 \cdot k_{air} \cdot L_{stud} \cdot W_{stud} \cdot R_{air} \cdot 10) \\
 Q_{stud} (kW) &= Q_{stud} \cdot (T_{air} - T_{air}) \\
 Q_{stud} (kW) &= 1 \cdot (k_{stud} / R_{stud} + R_{air} / 25) \cdot (R_{stud} + (R_{stud} - R_{stud}) / R_{stud} + R_{stud} / R_{stud}) \\
 Q_{stud} (kW) &= Q_{stud} \cdot R_{air} \cdot (T_{stud} - T_{air}) \cdot 1000 \\
 R_{stud} (m) &= R_{stud} \cdot R_{air} \cdot (Q_{stud} \cdot 1000) \cdot (T_{stud} - T_{air}) \\
 Q_{stud} (kW) &= 1 \cdot (k_{stud} / R_{stud} + R_{air} / 25) \cdot (R_{stud} + R_{stud} / R_{stud}) \\
 Q_{stud} (kW) &= Q_{stud} \cdot R_{air} \cdot (T_{stud} - T_{air}) \cdot 1000 \\
 T_{stud} (°C) &= Q_{stud} + Q_{stud} + R_{air} \cdot T_{air}
 \end{aligned}$$

3D half anode model

Of course, T_{airin} is also a user defined boundary condition in a 3D half anode model.

$$q = h (T_s - T_{airin})$$

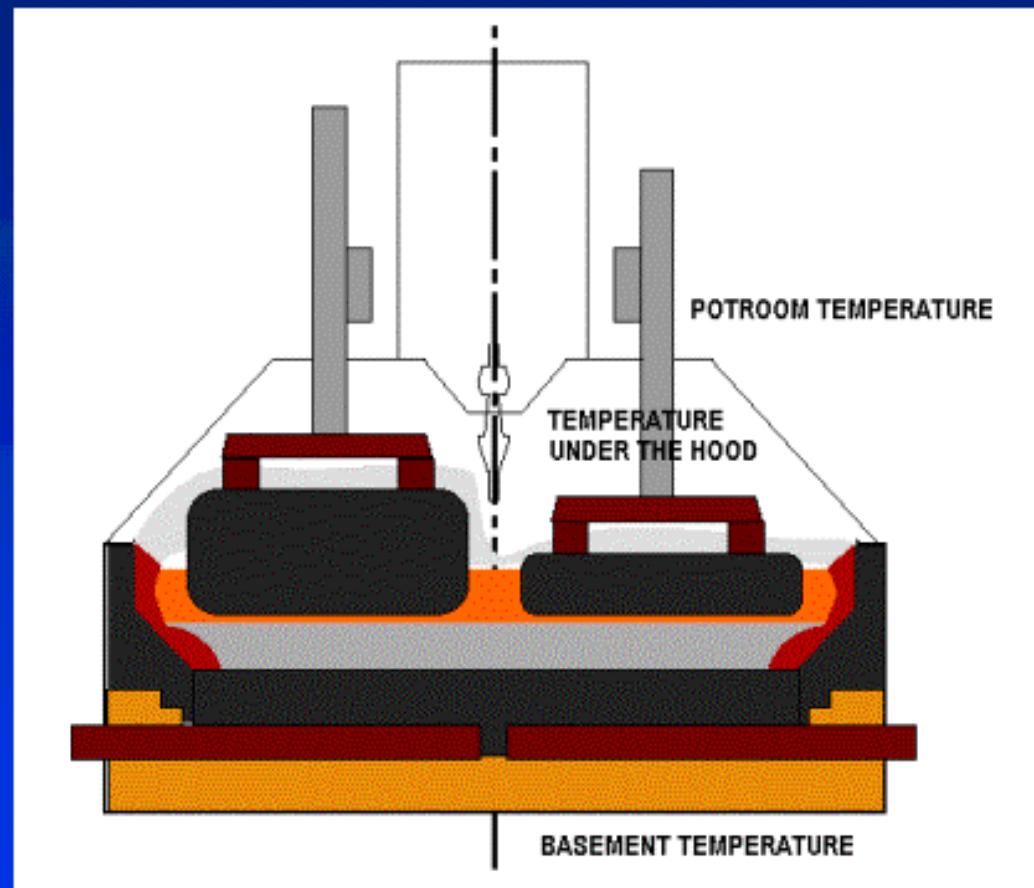


Temperature under the hood sub-model

Obviously, the temperature under the hood (T_{airin}) can be measured, but we expect that temperature to be function of many parameters like:

- the hood exhaust air rate
- the anode panel heat loss
- etc etc

Hence, it would be nice to develop a model in order to be able to predict its value.



Temperature under the hood sub-model

- First we must calculate the air drawn in under the hoods at potroom temperature, and combine it with the CO_2 and CO escaping at electrolyte temperature to produce a gas blend at temperature: T_{blend} .
- The CO of the mixture burns, generates heat, forms more CO_2 , and consumes O_2 from the air drawn in. Also, heat is generated by air burning of the anode forming additional CO_2 and consuming O_2 . The heats of combustion of CO and air burning of anode carbon plus the heat from the cover and anode stubs raise the temperature of the mixture of gases to temperature: T_{mix} .
- This gas mixture then extracts heat from the anode rods and rises to the exhaust temperature: T_{exh} .
- T_{airin} is calculated as the log mean of T_{mix} and T_{exh} , just as the log mean of inlet and outlet temperatures are used to calculate heat transfer in heat exchangers.

Heat capacities from fitted JANAF tables

$$C_p \text{ CO}_2 = 36.216 + 0.038894 T - 1.8743e-5 T^2$$

$$C_p \text{ CO} = 28.973 + 0.0050973 T + 6.0436e-7 T^2$$

$$C_p \text{ H}_2\text{O(g)} = 33.467 + 0.004365 T + 1.49e-5 T^2$$

$$C_p \text{ Air} = 29.066 + 0.0011449 T + 1.214e-5 T^2$$

$$C_p \text{ O}_2 = 29.236 + 0.00525 T + 1.32e-5 T^2$$

$$C_p \text{ N}_2 = 29.006 + 6.1987e-5 T + 1.2e-5 T^2$$

$$C_p \text{ Ar} = 20.786$$

In order to compute T_{blend} , T_{mix} and T_{exh} , the heat capacities of the gas mixtures is needed .

Calculating the wt % H₂O in the air

$$\text{Sat. \%H}_2\text{O} = 0.5544 + 0.024237 * T_{\text{amb}} + 0.00012594 * T_{\text{amb}}^2 + 2.4237\text{e-}5 * T_{\text{amb}}^3 + 6.25\text{e-}7 * T_{\text{amb}}^4$$

If T_{amb} is less than 12°C, then:

$$\text{Sat. \%H}_2\text{O} = 0.3125 * e^{(0.08759 * T_{\text{amb}})}$$

$$\text{Humid Factor} = (0.009096 + 0.0002196 * T_{\text{amb}}) * \text{RH} + (9.0377\text{e-}6 - 2.1963\text{e-}6 * T_{\text{amb}}) * \text{RH}^2$$

$$\text{\%H}_2\text{O in ambient air} = (\text{Sat. \%H}_2\text{O}) * (\text{Humid Factor})$$

The moisture content of the air drawn in has a significant effect on the heat capacity of the air.

Calculating the cell's evolution of CO and CO₂ and the air drawn into cell

$$\text{kg mol O}_2 / \text{min} = (\% \text{CE} / 100) * (\text{Cell kA} / 6432.3)$$

$$\text{NF} = 100 / (\% \text{CO}_2 + \% \text{CO} / 2)$$

$$\text{kg mol CO}_2 / \text{min} = \text{NF} * (\text{kg mol O}_2 / \text{min}) * (\% \text{CO}_2 / 100)$$

$$\text{kg mol CO} / \text{min} = \text{NF} * (\text{kg mol O}_2 / \text{min}) * (\% \text{CO} / 100)$$

$$\text{kg mol exh} / \text{min} = (\text{Std. m}^3 / \text{min exhaust}) / 22.41$$

$$\text{kg mol air} / \text{min} = ((\text{kg mol exh} / \text{min}) - (\text{kg mol CO}_2 / \text{min}) - 0.5 * (\text{kg mol CO} / \text{min})) * (1 - \% \text{H}_2\text{O} / 100)$$

$$\text{kg mol H}_2\text{O} / \text{min} = ((\text{kg mol exh} / \text{min}) - (\text{kg mol CO}_2 / \text{min}) - 0.5 * (\text{kg mol CO} / \text{min})) * \% \text{H}_2\text{O} / 100$$

Calculating Tblend

$$\text{AIR} = (\text{kg mol air} / \text{min}) * \text{Cp air}$$

$$\text{H}_2\text{O} = (\text{kg mol H}_2\text{O} / \text{min}) * \text{Cp H}_2\text{O}$$

$$\text{CO}_2 = (\text{kg mol CO}_2 / \text{min}) * \text{Cp CO}_2$$

$$\text{CO} = (\text{kg mol CO} / \text{min}) * \text{Cp CO}$$

Cp of CO₂ and CO are evaluated at:

$$T^{\circ}\text{C} = (\text{Telectrolyte} - \text{Tblend}) / \ln(\text{Telectrolyte} / \text{Tblend})$$

Cp of Air and H₂O(g) are evaluated at:

$$T^{\circ}\text{C} = (\text{Tamb} - \text{Tblend}) / \ln(\text{Tamb} / \text{Tblend})$$

$$\text{Tblend} = [\text{Telectrolyte} * \text{CO}_2 + \text{Telectrolyte} * \text{CO} + \text{Tamb} * \text{AIR} + \text{Tamb} * \text{H}_2\text{O}] / [\text{CO}_2 + \text{CO} + \text{AIR} + \text{H}_2\text{O}]$$

Calculating Qcombust and Qairburn

$$Q_{\text{combust}} (\text{kJ/min}) = (\text{kgmol CO} / \text{min}) * [283033 + 3.98 * T_{\text{blend}} - 7.493e-3 * (T_{\text{blend}})^2]$$

$$\text{Carbon} = \text{kg mol CO/min} + \text{kg mol CO}_2/\text{min}$$

$$\text{AirburnC} (\text{kg mol/min}) = \text{Carbon} * \% \text{ Air Burn} / 100$$

$$Q_{\text{airburn}} = \text{AirburnC} * [391996 - 9.876 * T_{\text{blend}} - 7.936e-5 * T_{\text{blend}}^2 + 16.265 * T_{\text{an top}} + 3.55e-3 * (T_{\text{an top}})^2]$$

Calculating Cp(blend) used to calculate the temperature rise of Qtop, Qcombust and Qairburn

To compute Cp(blend), the Cp of CO₂, N₂, Ar, O₂ and H₂O (g) are evaluated at:
 $T^{\circ}\text{C} = (T_{\text{mix}} - T_{\text{blend}}) / \ln(T_{\text{mix}} / T_{\text{blend}})$

$$\begin{aligned} \text{Cp}(\text{blend}) = & (0.78112 * (\text{kg mol air} / \text{min}) / (\text{kg mol exh} / \text{min}) * \text{Cp N}_2 + \\ & (0.00934 * (\text{kg mol air} / \text{min}) / (\text{kg mol exh} / \text{min}) * \text{Cp Ar} + \\ & [\text{kg mol H}_2\text{O}(\text{g})] / (\text{kg mol exh} / \text{min}) * \text{Cp H}_2\text{O}(\text{g}) + \\ & [(\text{kg mol CO}_2 / \text{min}) + (\text{kg mol CO} / \text{min}) + \text{AirburnC}] / \\ & (\text{kg mol exh} / \text{min}) * \text{Cp CO}_2 + \\ & [0.20954 * (\text{kg mol air} / \text{min}) - 0.5 * (\text{kg mol CO} / \text{min}) - \text{AirburnC}] / \\ & (\text{kg mol exh} / \text{min}) * \text{Cp O}_2 \end{aligned}$$

Calculating Cp(mix) used to calculate ΔT rise caused by removing heat from the anode rods

To compute Cp(mix), the Cp of CO₂, N₂, Ar, O₂ and H₂O (g) are evaluated at the temperature T_{airin}.

$$\begin{aligned} \text{Cp(mix)} = & (0.78112 * (\text{kg mol air} / \text{min}) / (\text{kg mol exh} / \text{min}) * \text{Cp N}_2 + \\ & (0.00934 * (\text{kg mol air} / \text{min}) / (\text{kg mol exh} / \text{min}) * \text{Cp Ar} + \\ & [\text{kg mol H}_2\text{O(g)}] / (\text{kg mol exh} / \text{min}) * \text{Cp H}_2\text{O(g)} + \\ & [(\text{kg mol CO}_2 / \text{min}) + (\text{kg mol CO} / \text{min}) + \text{AirburnC}] / \\ & (\text{kg mol exh} / \text{min}) * \text{Cp CO}_2 + \\ & [0.20954 * (\text{kg mol air} / \text{min}) - 0.5 * (\text{kg mol CO} / \text{min}) - \text{AirburnC}] / \\ & (\text{kg mol exh} / \text{min}) * \text{Cp O}_2 \end{aligned}$$

Calculating T_{mix} , T_{exh} and T_{airin}

$$T_{mix} = T_{blend} + [(Q_{top} * 60) + Q_{combust} + Q_{airburn}] / [(kg \text{ mol exh/min}) * C_p(\text{blend})]$$

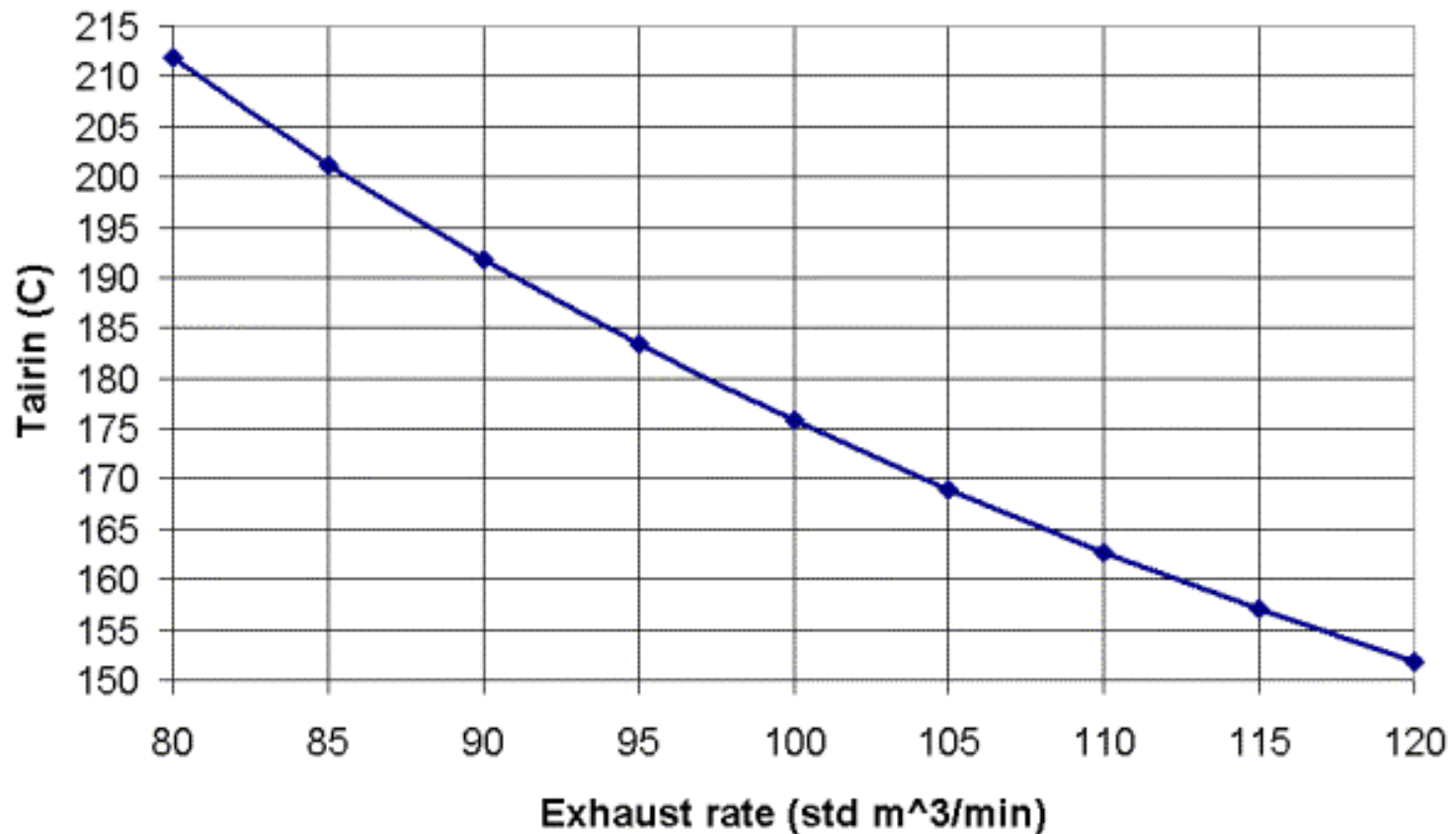
$$\Delta T_{rise} = (Q_{rods} * 60) / [(kg \text{ mol exh/min}) * C_p(\text{mix})]$$

$$T_{exh} = T_{mix} + \Delta T_{rise}$$

$$T_{airin} = (T_{exh} - T_{mix}) / \ln (T_{exh} / T_{mix})$$

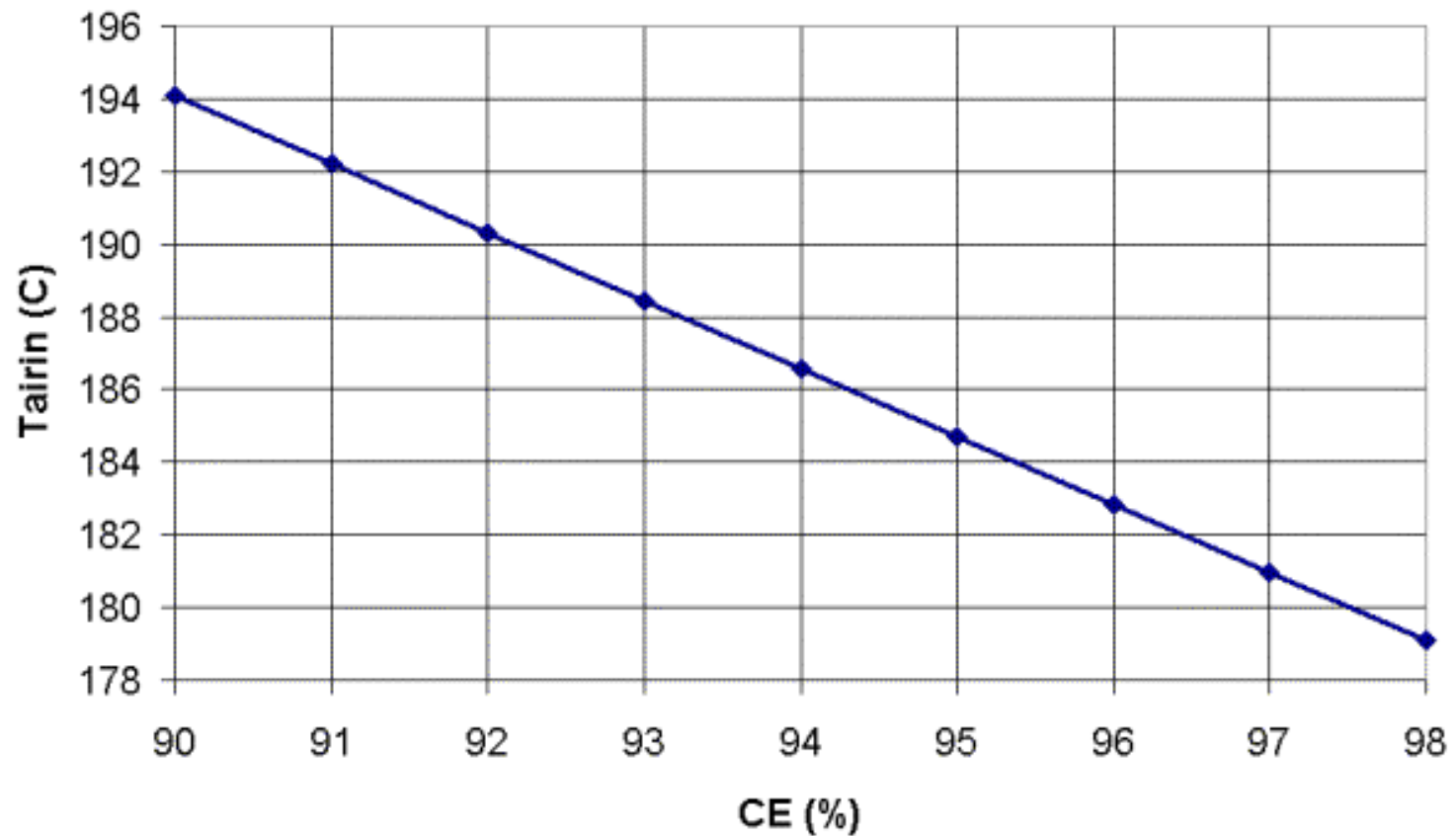
Analysis of results

Tairin vs Exhaust rate

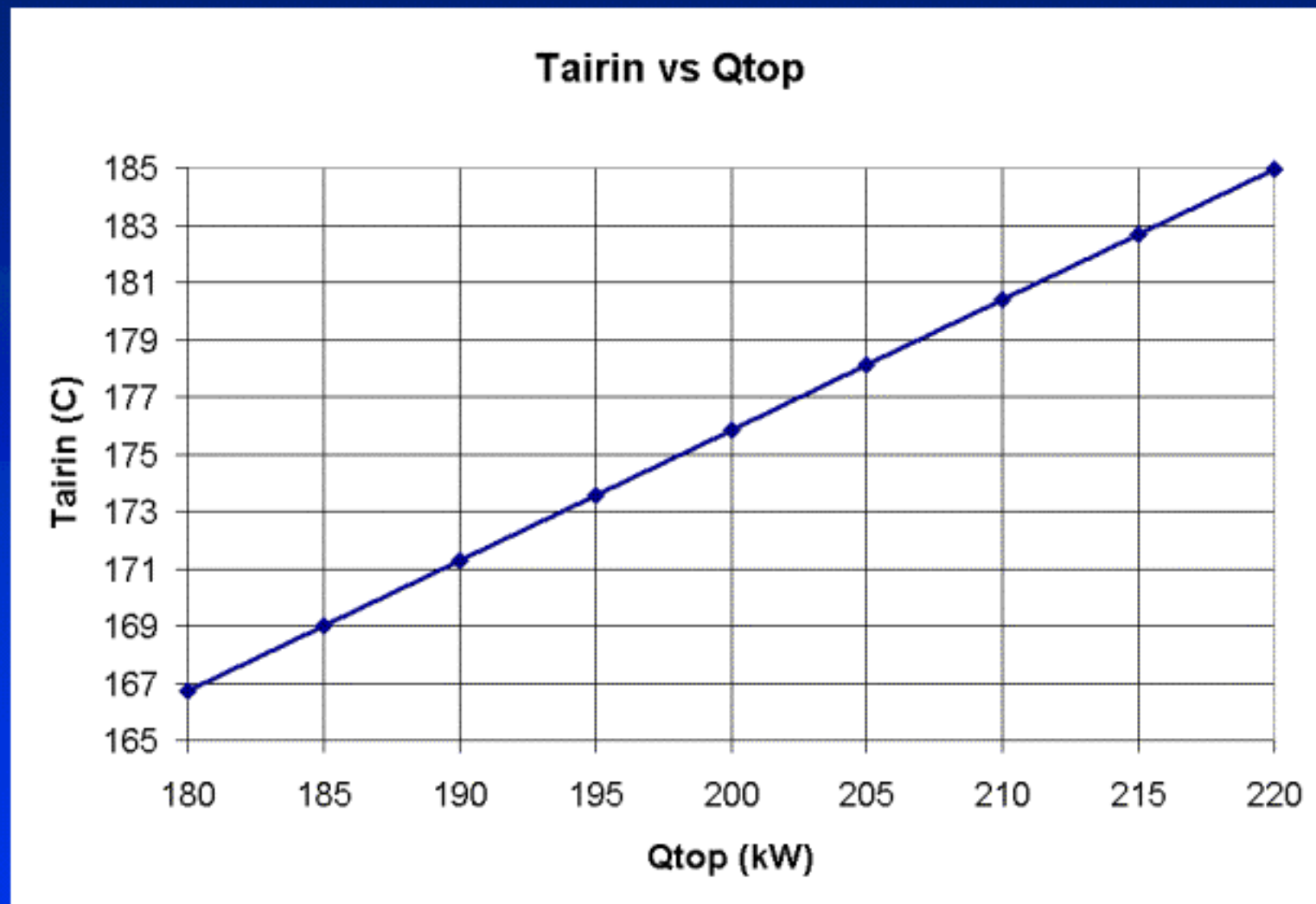


Analysis of results

Tairin vs CE

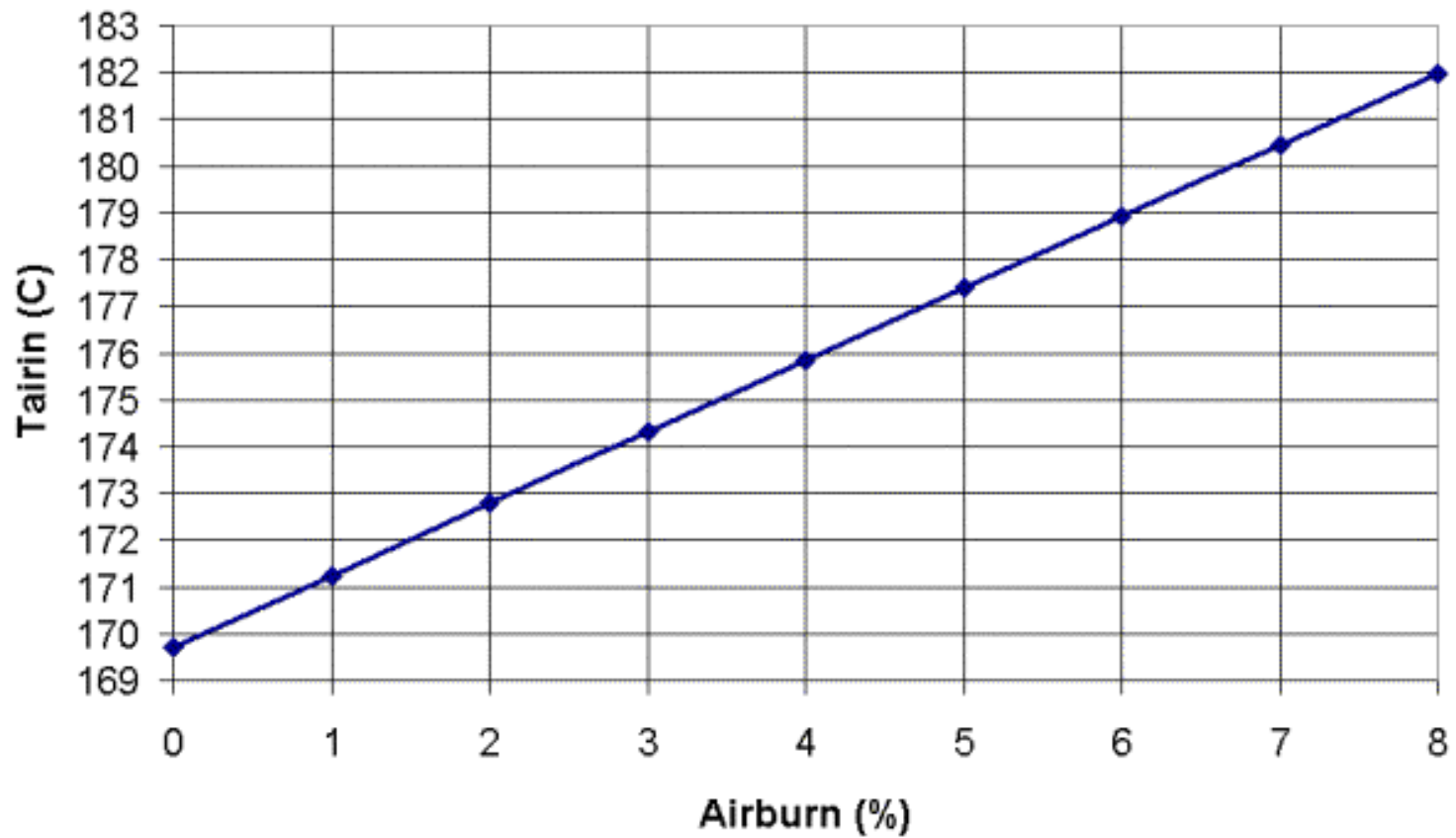


Analysis of results



Analysis of results

Tairin vs Airburn



Applications

DYNA/MARC: Advance Anode Panel Heat Loss

Advance Anode Panel Heat Loss

Anode Stud Diameter	0.18	m
Number of Stud(s) per Anode	3	
Average Thickness of Cast Iron around Studs	0.02	m
Stud Hole Depth	0.14	m
Average Carbon Thickness under the Stud at Mid Anode Life	0.24	m
Thermal Conductivity of the Anode Carbon	4	W/m °C
Average Thickness of Cover Material Above Anode	0.16	m
Thermal Conductivity of Cover Material at Low Temperature	0.4	W/m °C
Thermal Conductivity of Cover Material at High Temperature	2	W/m °C
Temperature of the Cover Material Thermal Conductivity Transition	770	°C
Reference Anode Panel Studs Yokes and Rods Heat Loss	132.126306	kW

Average Temperature of the Air Under the Hood

Used Defined **Computed**

Average Temperature of the Air Under the Hood	176.402139	°C
Hood Exhaust Air Rate	100	std m3/min
Relative Humidity of the Potroom Air	10	%
% of the Carbon which Air Burns	16	%

Tairin Calculator

175.849

Top °C	975
Tair °C	30
AMP kA	300
Exhaust std m3/min	100
Qtop kW	200
Qrods kW	30
CE %	94
CE Short %	1
Relative Humidity %	10
Tanobk °C	1305
Airburn %	4

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Conclusions

- A method has been presented to estimate the temperatures found under the hood of a prebaked anode cell.
- The equations presented in this paper now form a new sub-model in the lump parameters+ dynamic cell simulator called Dyna/Marc version 1.8.
- The equations presented in this paper have also been coded into a little freeware program that you can download from the GeniSim Web site at www.genisim.com/download/tairin.exe.
- Both applications will let you easily estimate the gas temperature distribution under the hood.