Calculating Temperatures Under Hood of a Prebake Anode Cell

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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.
Anode panel heat loss sub-model

As seen before, the anode panel heat loss sub-model requires the user to specify the average air temperature under the hood (Tairin).
Of course, Tairin is also a user defined boundary condition in a 3D half anode model.

\[ q = h \left( T_s - T_{\text{Tairin}} \right) \]
Temperature under the hood sub-model

Obviously, the temperature under the hood (Tairin) can be measured, but we expect that temperature to be a 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: $T_{\text{blend}}$.

- 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: $T_{\text{mix}}$.

- This gas mixture then extracts heat from the anode rods and rises to the exhaust temperature: $T_{\text{exh}}$.

- $T_{\text{airin}}$ is calculated as the log mean of $T_{\text{mix}}$ and $T_{\text{exh}}$, 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 % $\text{H}_2\text{O}$ in the air

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

If Tamb is less than 12°C, then:

Sat. $\%\text{H}_2\text{O} = 0.3125 \times (0.08759 \times \text{Tamb})$

Humid Factor = (0.009096 + 0.0002196 \times \text{Tamb}) \times \text{RH} + (9.0377e-6 - 2.1963e-6 \times \text{Tamb}) \times \text{RH}^2

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

kg mol O₂/min = ( %CE / 100 ) * ( Cell kA / 6432.3 )

NF = 100 / ( %CO₂ + %CO / 2 )

kg mol CO₂ / min = NF * (kg mol O₂ /min ) * ( %CO₂ / 100)

kg mol CO / min = NF * (kg mol O₂ /min ) * ( %CO / 100)

kg mol exh / min = (Std. m³ / min exhaust) / 22.41

kg mol air / min = ( (kg mol exh / min) – (kg mol CO₂ / min) – 0.5 * (kg mol CO / min) ) * ( 1 - %H₂O / 100 )

kg mol H₂O / min = ( (kg mol exh / min) – (kg mol CO₂ / min) – 0.5 * (kg mol CO / min) ) * %H₂O / 100
Calculating Tblend

\[ \text{AIR} = (\text{kg mol air / min}) \times \text{Cp air} \]
\[ \text{H}_2\text{O} = (\text{kg mol H}_2\text{O / min}) \times \text{Cp H}_2\text{O} \]
\[ \text{CO}_2 = (\text{kg mol CO}_2 / \text{min}) \times \text{Cp CO}_2 \]
\[ \text{CO} = (\text{kg mol CO / min}) \times \text{Cp CO} \]

\text{Cp of CO}_2 \text{ and CO are evaluated at:}
\[ T^\circ C = (\text{Telectrolyte} - \text{Tblend}) / \ln(\text{Telectrolyte} / \text{Tblend}) \]

\text{Cp of Air and H}_2\text{O(g) are evaluated at:}
\[ T^\circ C = (\text{Tamb} - \text{Tblend}) / \ln(\text{Tamb} / \text{Tblend}) \]

\[ \text{Tblend} = \left[ \text{Telectrolyte} \times \text{CO}_2 + \text{Telectrolyte} \times \text{CO} + \text{Tamb} \times \text{AIR} + \text{Tamb} \times \text{H}_2\text{O} \right] / \left[ \text{CO}_2 + \text{CO} + \text{AIR} + \text{H}_2\text{O} \right] \]
Calculating $Q_{\text{combust}}$ and $Q_{\text{airburn}}$

$$Q_{\text{combust}} \text{ (kJ/min)} = (\text{kgmol CO / min}) \times \left[ 283033 + 3.98 \times T_{\text{blend}} - 7.493 \times 10^{-3} \times (T_{\text{blend}})^2 \right]$$

Carbon = kg mol CO/ min + kg mol CO$_2$/ min

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

$Q_{\text{airburn}} = \text{AirburnC} \times \left[ 391996 - 9.876 \times T_{\text{blend}} - 7.936 \times 10^{-5} \times T_{\text{blend}}^2 + 16.265 \times \text{Tan top} + 3.55 \times 10^{-3} \times (\text{Tan top})^2 \right]$
Calculating $C_p(\text{blend})$ used to calculate the temperature rise of $Q_{\text{top}}, Q_{\text{combust}}$ and $Q_{\text{airburn}}$

To compute $C_p(\text{blend})$, the $C_p$ of CO$_2$, N$_2$, Ar, O$_2$ and H$_2$O (g) are evaluated at:

$$T^\circ C = (T_{\text{mix}} - T_{\text{blend}}) / \ln(T_{\text{mix}} / T_{\text{blend}})$$

$$C_p(\text{blend}) = (0.78112 * (\text{kg mol air} / \text{min}) / (\text{kg mol exh} / \text{min}) * C_p \text{ N}_2 +$$
$$ (0.00934 * (\text{kg mol air} / \text{min}) / (\text{kg mol exh} / \text{min}) * C_p \text{ Ar} +$$
$$ [\text{kg mol H}_2\text{O(g)}] / (\text{kg mol exh} / \text{min}) * C_p \text{ H}_2\text{O(g)} +$$
$$ [ (\text{kg mol CO}_2 / \text{min}) + (\text{kg mol CO} / \text{min}) + \text{AirburnC } ] /$$
$$ (\text{kg mol exh} / \text{min}) * C_p \text{ CO}_2 +$$
$$ [ 0.20954 * (\text{kg mol air} / \text{min}) - 0.5 * (\text{kg mol CO} / \text{min}) - \text{AirburnC } ] /$$
$$ (\text{kg mol exh} / \text{min}) * C_p \text{ O}_2$$
Calculating $C_p(\text{mix})$ used to calculate $\Delta T$ rise caused by removing heat from the anode rods

To compute $C_p(\text{mix})$, the $C_p$ of CO$_2$, N$_2$, Ar, O$_2$ and H$_2$O (g) are evaluated at the temperature $T_{air}$.

$$C_p(\text{mix}) = (0.78112 \times \frac{\text{kg mol air/\text{min}}}{\text{kg mol exh/\text{min}}} \times C_p \text{ N}_2 +$$
$$ (0.00934 \times \frac{\text{kg mol air/\text{min}}}{\text{kg mol exh/\text{min}}} \times C_p \text{ Ar} +$$
$$ [\text{kg mol H}_2\text{O(g)}] / (\text{kg mol exh/\text{min}}) \times C_p \text{ H}_2\text{O(g)} +$$
$$ [ (\text{kg mol CO}_2 / \text{min}) + (\text{kg mol CO/ \text{min}}) + \text{AirburnC} ] /$$
$$ (\text{kg mol exh/\text{min}}) \times C_p \text{ CO}_2 +$$
$$ [ 0.20954 \times \frac{\text{kg mol air/\text{min}}}{\text{kg mol CO/\text{min}}} - 0.5 \times (\text{kg mol CO/ \text{min}}) - \text{AirburnC} ] /$$
$$ (\text{kg mol exh/\text{min}}) \times C_p \text{ O}_2$$
Calculating $T_{mix}$, $T_{exh}$ and $T_{airin}$

\[
T_{mix} = T_{blend} + \left[ \frac{(Q_{top} \times 60) + Q_{combust} + Q_{airburn}}{(kg \ mol \ exh/min) \times Cp(\text{blend})} \right]
\]

\[
\Delta T_{rise} = \left( \frac{Q_{rods} \times 60}{(kg \ mol \ exh/min) \times Cp(\text{mix})} \right)
\]

\[
T_{exh} = T_{mix} + \Delta T_{rise}
\]

\[
T_{airin} = \frac{(T_{exh} - T_{mix})}{\ln(T_{exh} / T_{mix})}
\]
Analysis of results

Tairin vs Exhaust rate

Exhaust rate (std m^3/min)

Tairin (C)
Analysis of results

Tairin vs CE

Tairin (C)

90 91 92 93 94 95 96 97 98

CE (%)
Analysis of results

Tairin vs Qtop

Tairin (°C)

Qtop (kW)
Analysis of results

Tairin vs Airburn

Airburn (%) vs Tairin (°C)
Applications

DYNA/MARC: 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: ✔
- 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

- 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
- Tanbkk °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.