Approved for Public Release

ANSYS 17.2 Thermal Verification

2017 UTSR Fellow

FLORIDA TURBINE TECHNOLOGIES

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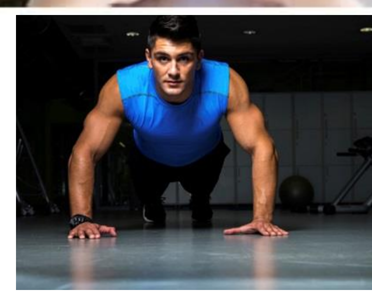
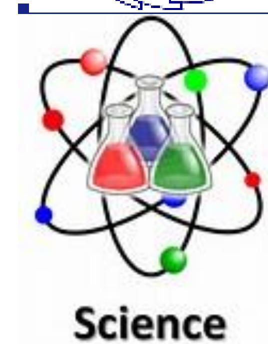
Heat Transfer Intern

- Born in Miami, FL
- Student from the University of Central Florida (UCF)
- Graduated with Bachelor's degree in Mechanical Engineering in December 2016
- Research Assistant at Center for Advanced Turbomachinery and Energy Research (CATER)
- Currently pursuing a Masters' degree ~ May/August 2018
- Fellow/Intern from the University Turbine System Research Program
- Hobbies





Overview

- Introduction
- Building Up The Model
- Macro To Apply Boundary Conditions
- Results
- Hand Calculations
- Post Processing of Results
- Conclusion

Introduction

- FTT utilizes ANSYS to perform structural and thermal analyses
- FTT upgrades to newly available ANSYS versions periodically depending on the overall improvements over older versions
- One of the main reasons to upgrade is due to the lack of support from ANSYS over older versions so it is only practical to upgrade
- Before upgrading, it would be valuable for a verification process to take place that checks key features and capabilities along with comparison to older versions

Methodology

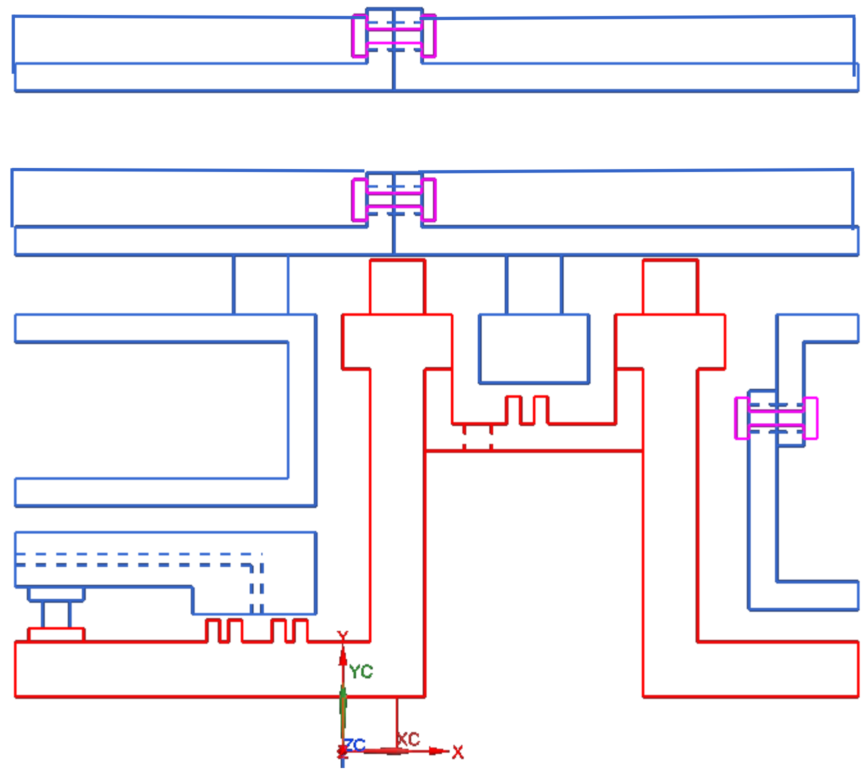
- Full fluid network as appropriate
- Aero BCs are fictitious (Not controlled/proprietary)
- Secondary flows estimated on %G1C basis (% of engine compressor inlet flow)
- HTCs applied using order-of-magnitude rule of thumb (i.e. not actually calculated)
- Steady State (SS) and Transient Analysis

Success Criteria

- Post-processing will assume that the baseline version 14.5 (to which the new version 17.2 is being compared) is entirely reliable
- Check transient time selection
  - Plot both time points
  - Compare Oscillation limit (OSLM) for all timepoints which express the stability of results
    - Success if OSLM < 1
    - Failure if OSLM > 1 for more than 1 second
- Run Macro
  - Compares all nodal temperatures at timepoints as defined by baseline analysis (i.e. if timepoints aren't identical, new transient thermals will be interpolated)
  - Writes out maximum ΔTemp vs time
    - Success [ΔT<1]; failure [ΔT>1]
    - If criteria not met, investigate

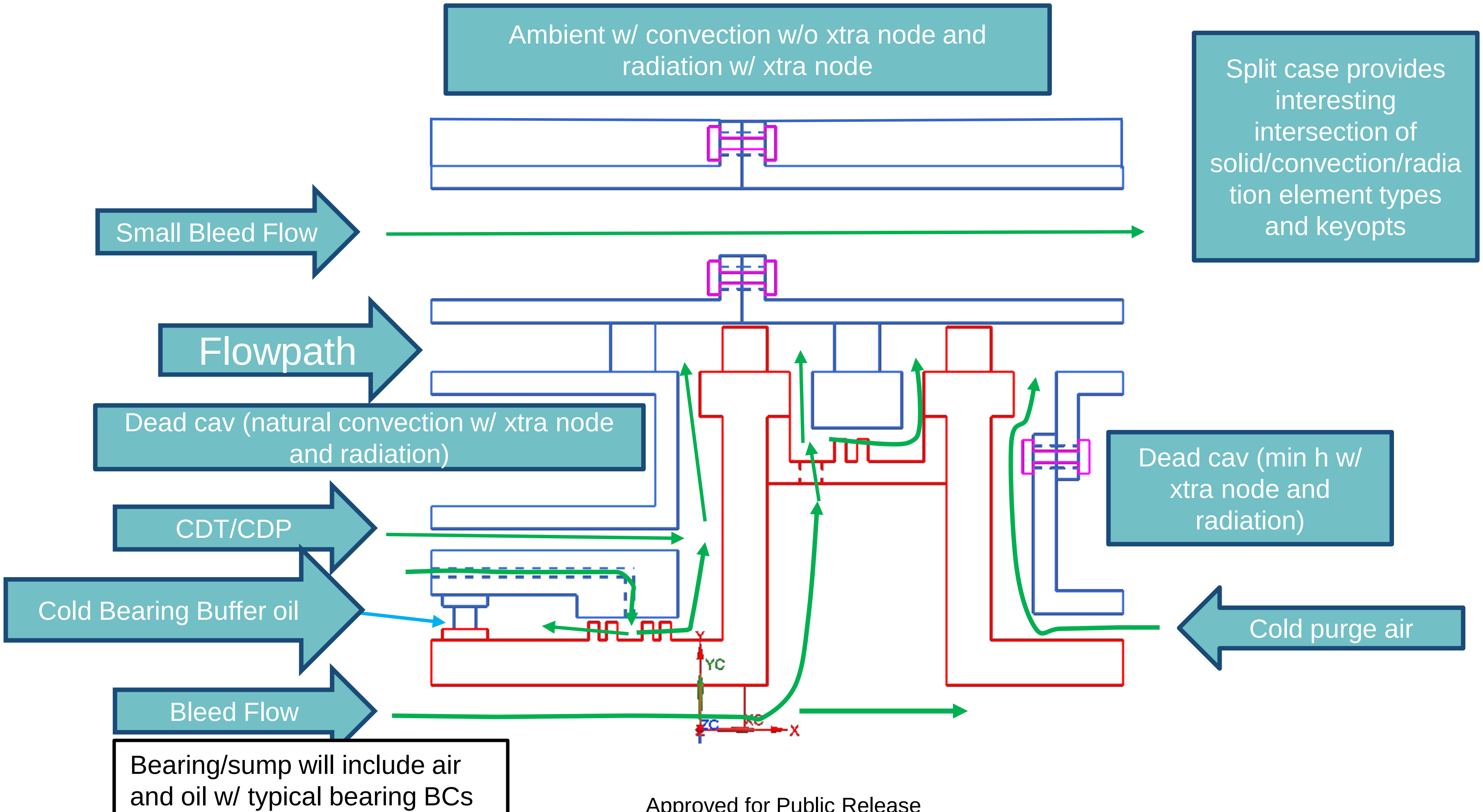
Project Requirements

- 2D Model
  - Conduction
    - Axisymmetric
    - Plane with thickness
  - Convection
    - W/ Xtra node
    - W/out Xtra node
    - In holes
  - Radiation
    - To a node
    - To a surface
  - Advection
    - W/ standard convection
    - W/ multiple fluids
    - W/ windage and surface heat generation
    - W/ Radiation
  - Contact
    - High TCC
    - Low TCC



2D Model Overview

- General model of a simple turbine

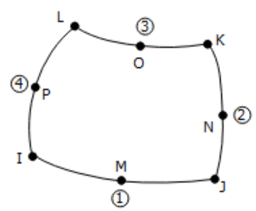


Building Up The model

Element Attributes

- Element Type
  - PLANE77
    - Elements for metal components
    - Axisymmetric or Plane w/ thickness
  - SURF151
    - To model convection/advection on surfaces w/ or w/o extra node
    - Radiation to a node
  - SURF152
    - Same as surf151 but to plane w/ thickness elements
  - FLUID116
    - To model fluid flow
  - TARGE169 & CONTACT172
    - To specify contact resistance b/w parts
  - LINK33 & MATRIX50
    - To model radiation in an enclosure
- Material
  - *Material properties were given*
  - 2 – air, 3 – oil, 718 – Nickel Based Alloy
  - Density $[\rho]$
  - Specific Heat $[cp]$
  - Viscosity $[\mu]$
  - Thermal Conductivity $[k]$
  - Emissivity $[\epsilon]$
  - Thermal Expansion $[1/°\mathrm{F}]$
- Real Constants
  - Thickness
  - Angular velocity
  - Swirl factor
  - Gravitational constant
  - Joule constant
  - Stephan Boltzmann constant
  - View/Form factor
  - Etc.…

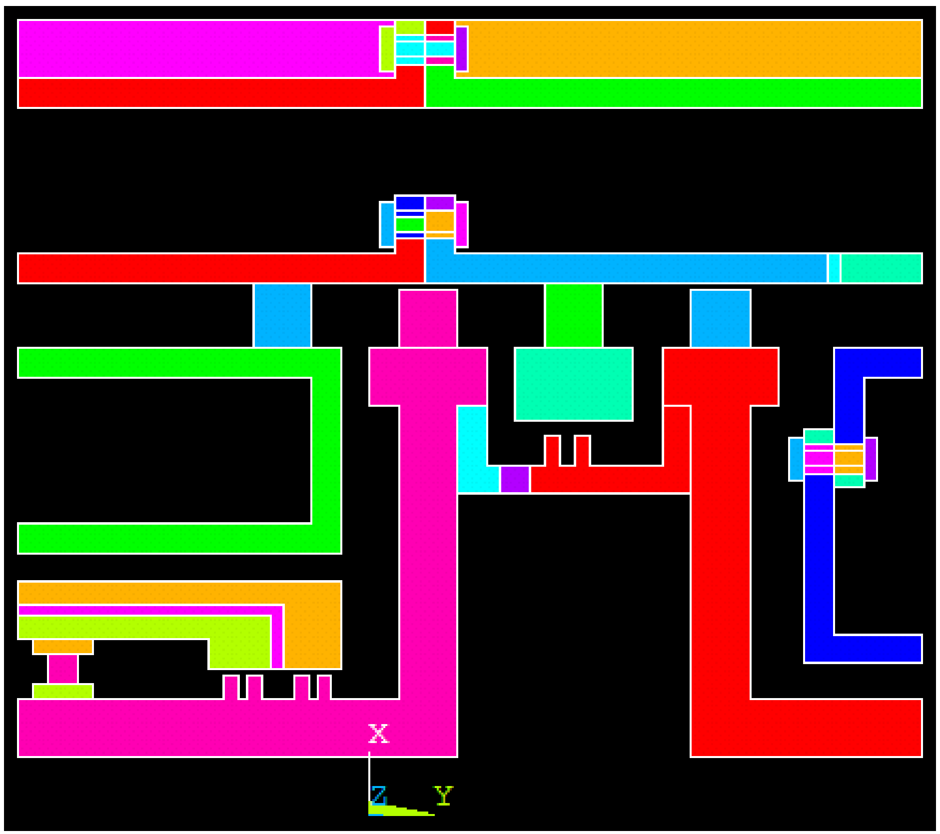
Complete Model (Area & Element Plot)

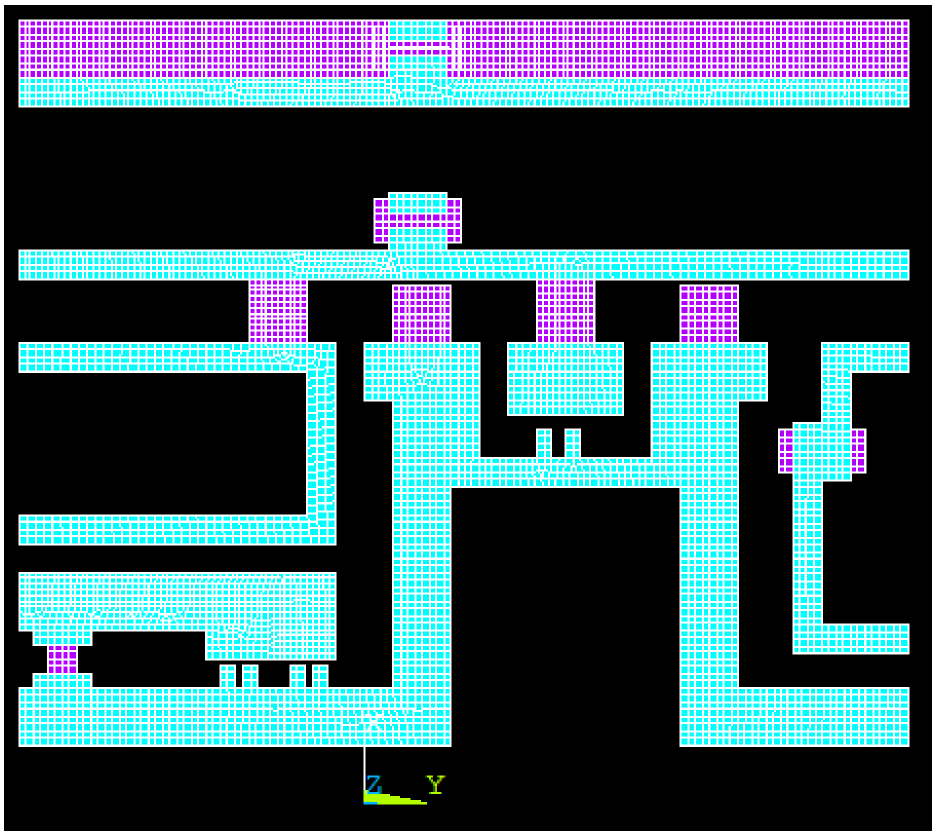


Elements: 6,342
Nodes: 21,028

Plane w/ thickness

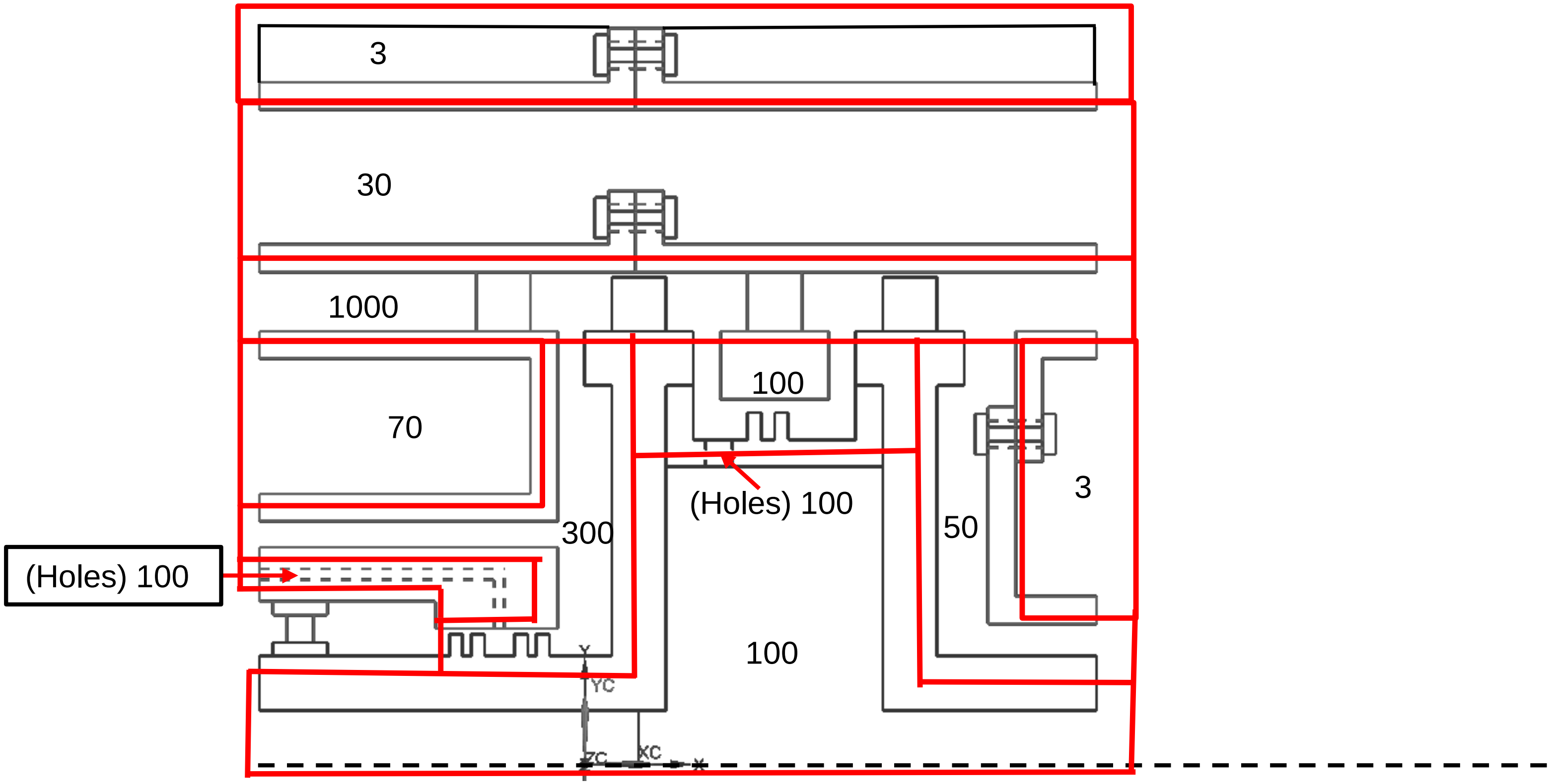
Axisymmetric





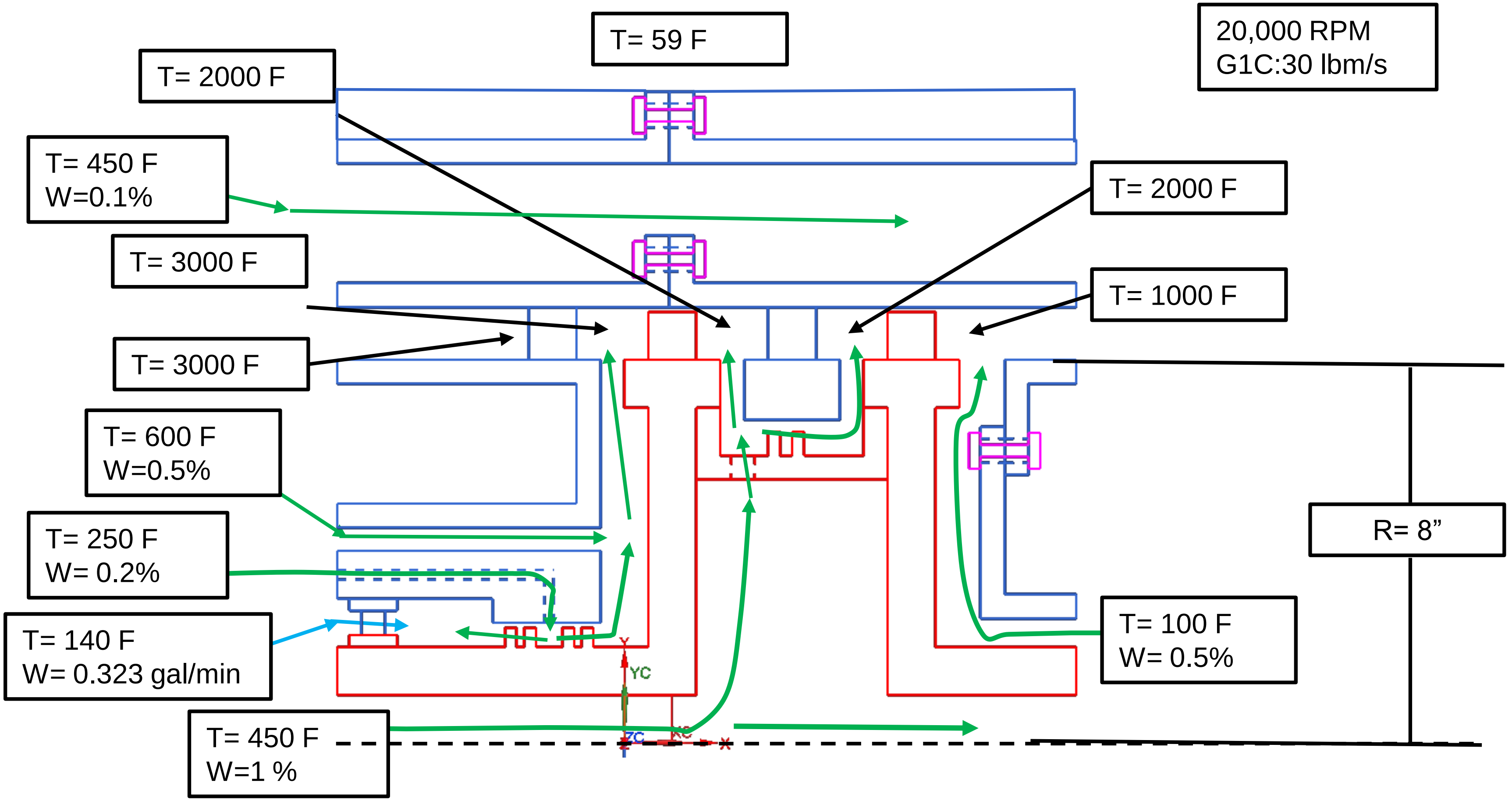
2D Model Overview

- HTCs are order-of-magnitude values (no proprietary correlations used)
- Boxes show HTCs in BTU/hr/ft^2/F



Entry Temperatures & Flow Rates

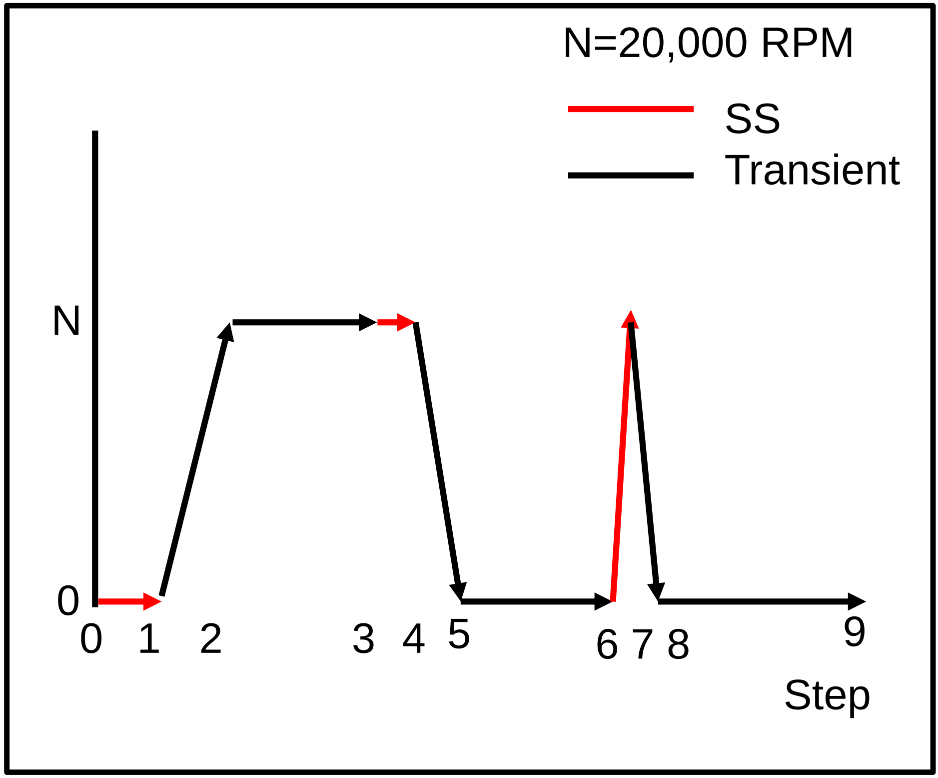
- Model generically mimics the features of a simple turbine
- Aero Design Point (ADP) values at 20,000 RPM



Macro Creation for boundary conditions

SS/Transient

- Step 1; 0.01 s
  – SS 0 RPM
- Step 2; 30 s
  – End Transient Accel
- Step 3; 3629.999 s
  – End Transient Dwell @ N RPM
- Step 4; 3630 s
  – SS ADP
- Step 5; 3660 s
  – End Transient Decel
- Step 6; 7260 s
  – End Transient Dwell @ 0 RPM
- Step 7; 7261 s
  – SS ADP Accel
- Step 8; 7264 s
  – End Transient Estop Decel
- Step 9; 10864 s
  – Post Estop Transient Dwell @ 0 RPM



Macro Creation

- Created a macro to be read into ANSYS that would apply all necessary BC's and solve transiently/SS
- Coded in ANSYS Parametric Design Language (APDL)
- Used *dim command to create several tables to define all BC's with respect to time
  - Flow rate
  - Upstream temperature to all entry fluid nodes
  - Heat generation on the fluid nodes and bearing
  - Bulk temperature and HTC values to all locations where SURF151 and SURF152 were implemented
  - Speed in rad/s for the different time intervals
- Created arrays to state when to run transiently or SS for a total of 9 load steps
- All BCs are parameterized to change linearly b/w load steps by ANSYS
- ADP values at 20,000 RPM and standard/min values at 0 RPM

Macro Creation

- A Do-Loop is utilized to define every BC accordingly to whether Transient or SS solution type is selected
- A variable “curtime” was defined to be the current runtime, which linked every BC with respect to that current time to then be applied to all mentioned parameters
- Most real constants related to FLUID116 and SURF151/152 are defined in the loop
  - Angular acceleration, gravitational constant, and swirl factors

Units and Conversions

- $1\ sling = [slug * \frac{ft}{in}]$
  - (simplifying a group of units)
- $1\ lbf = 1\ slug * \frac{ft}{s^2}$
- $1\ slug = 32.17\ lbm$
- $\rho = [\ \frac{sling}{in^3}]$
- $cp = \frac{BTU}{sling*°F}$
- $\mu = \frac{sling}{in*s}$
- $k = \frac{BTU}{s*in*°F}$
- $Q = \frac{BTU}{s}$
- $Q'' = \frac{BTU}{s*in^2*°F}$
- $W = \frac{lbm}{s} * \left(\frac{1}{386}\right) = \frac{sling}{s}$
- $\omega = \frac{2\pi N}{60}$
- Temperature; °F, R
- HTC = $\frac{BTU}{hr*ft^2*°F} * \left(\frac{1}{518400}\right) = \frac{BTU}{s*in^2*°F}$

Equations

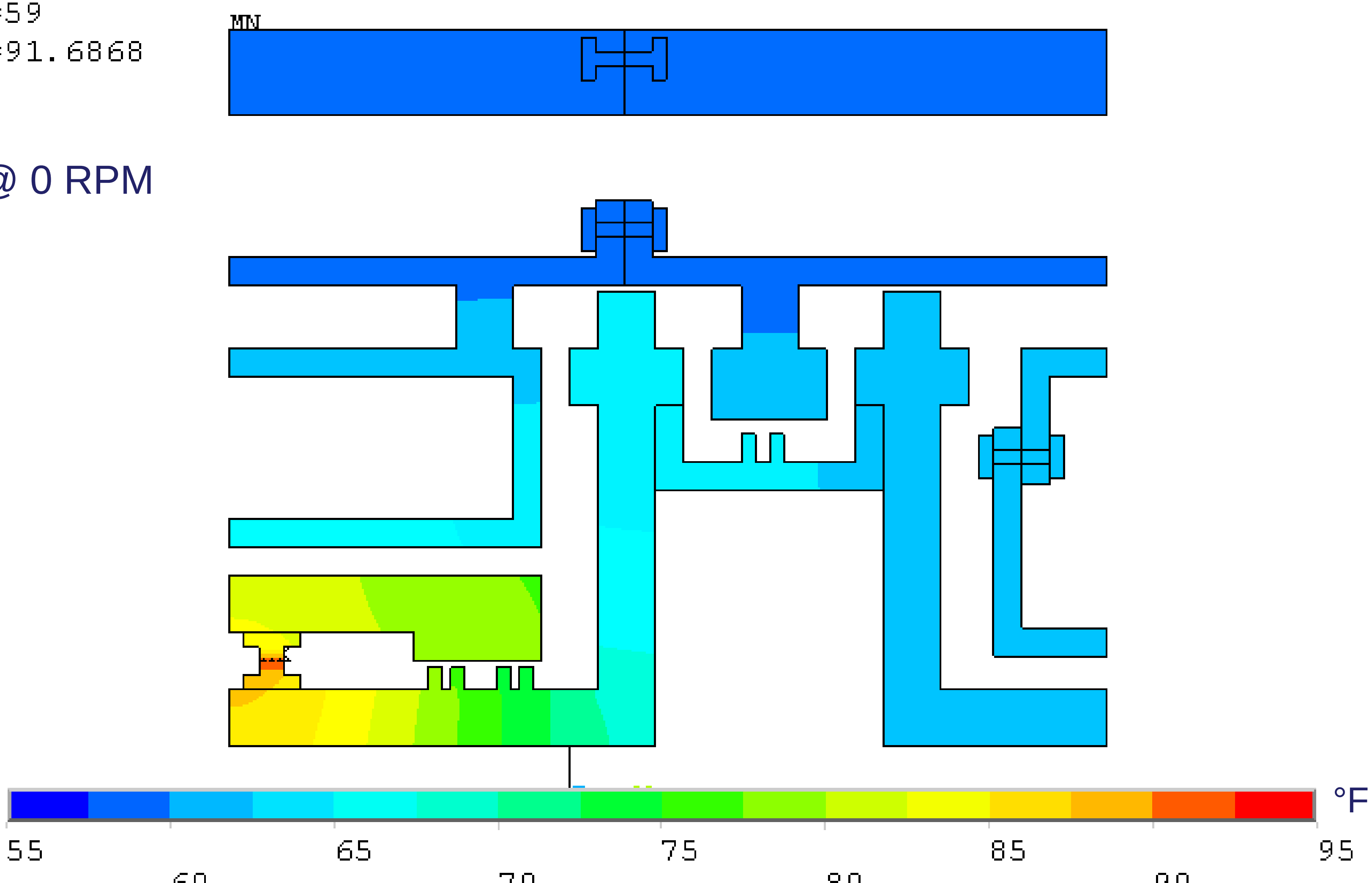
- $Q\_conv = HTC * As * (Ts - Tbulk)$
- $Q\_cond = K * Ac * \frac{T2-T1}{\Delta x}$
- $Q\_rad = \sigma * As * \epsilon * (Ts^4 - Tsurr^4)$
- $Trel = T\_tot+U^2*(1-2xk)/(2*g*J*Cp)$
- $T = T_\infty + (Ti - T_\infty)*e^{-(t/\tau)}$
- $\tau = \frac{\rho * V * cp}{h * As}$
- $T_{eff} = \frac{T_1 * A_1 + T_2 * A_2}{A_1 + A_2}$
- $\frac{1}{U * Atot} = \frac{1}{h_1 * A_1} + \frac{1}{TCC * A_2}$
  - $TCC = thermal\ contact\ conductance$
- $\tau eff = \frac{\rho * V * cp}{U * A_{tot}}$

Metal Nodal Temp DOF @ All Load Steps

Load Step 1 @ 0.01 Seconds

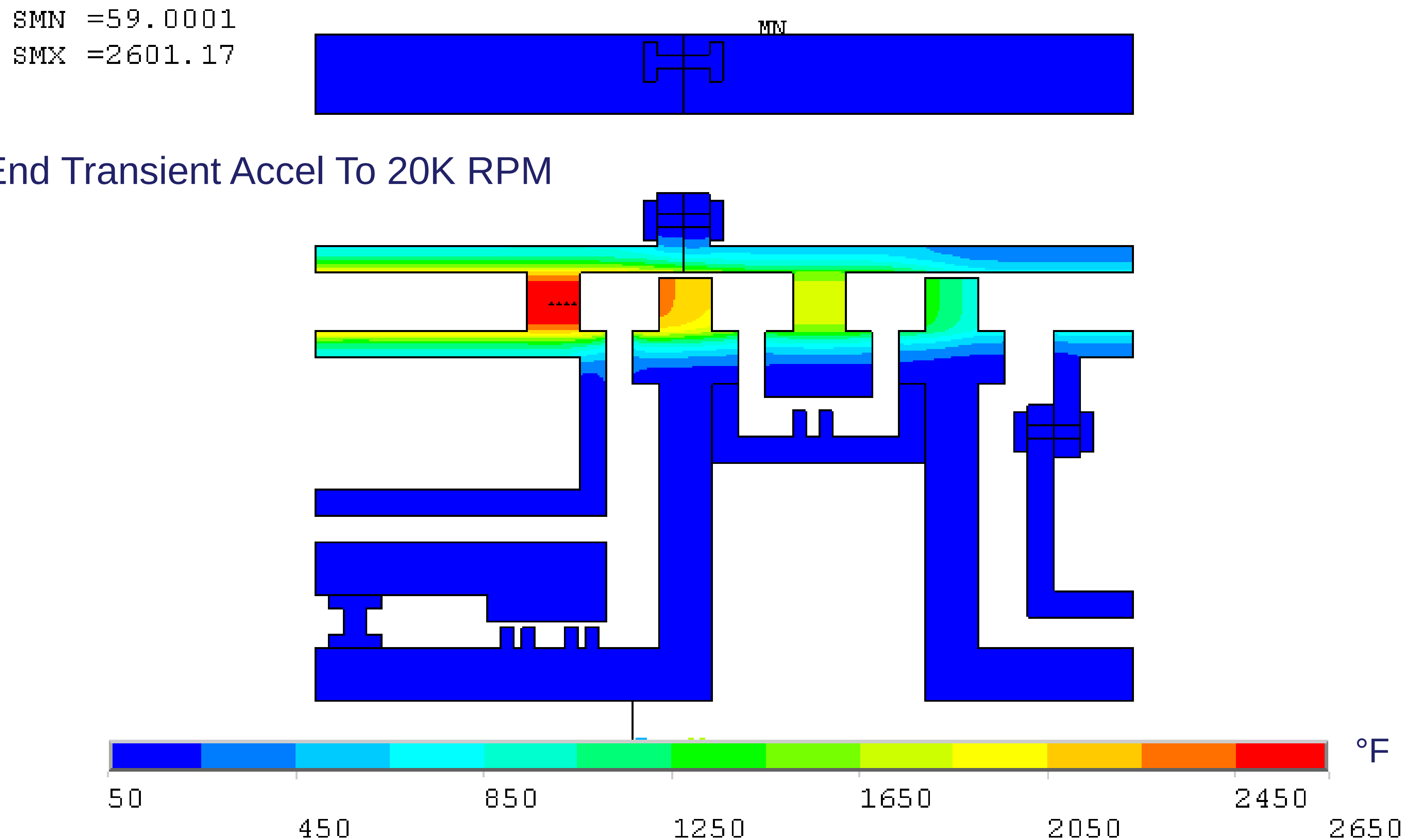
SMN =59
SMX =91.6868

SS @ 0 RPM

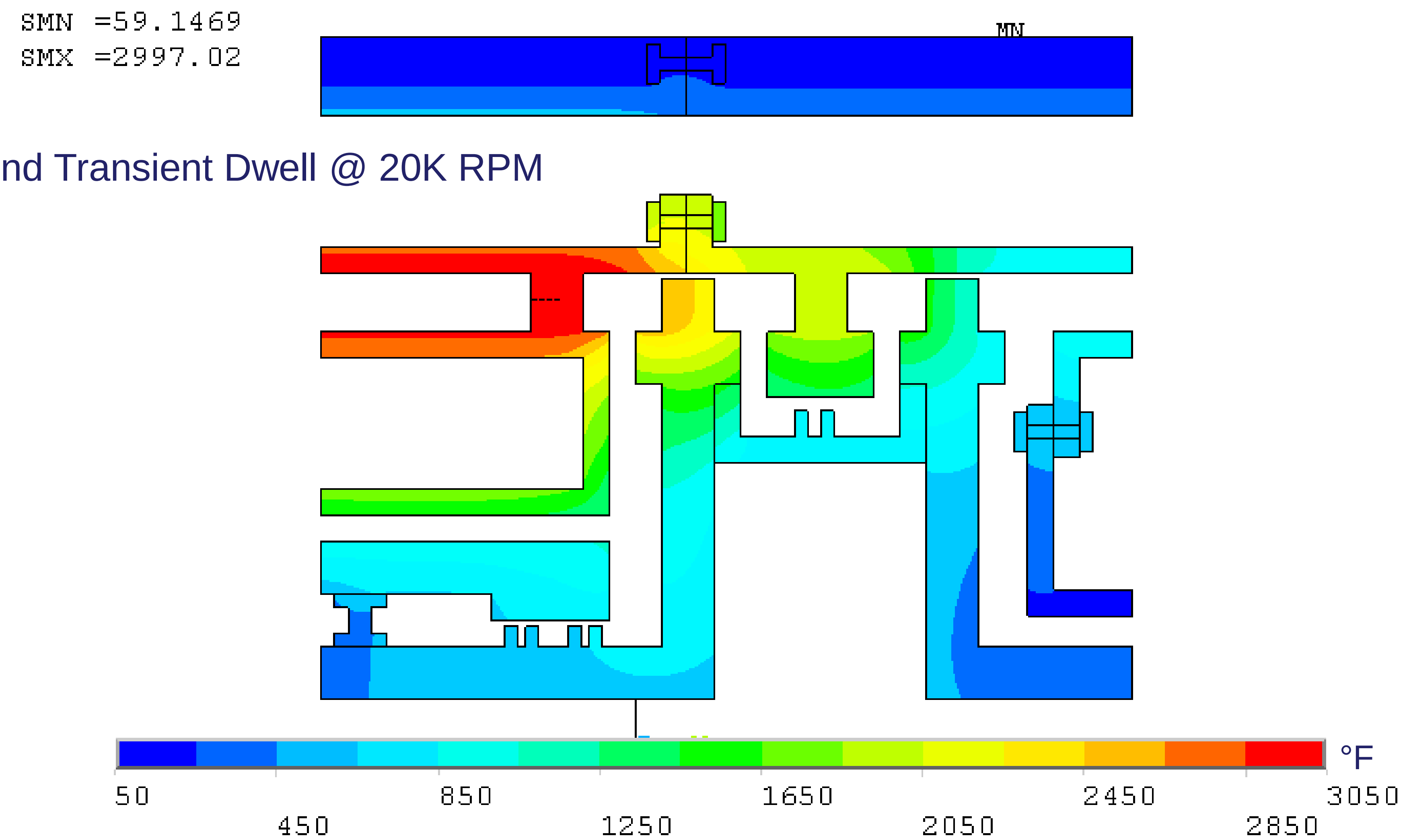


Load Step 2 @ 30 Seconds

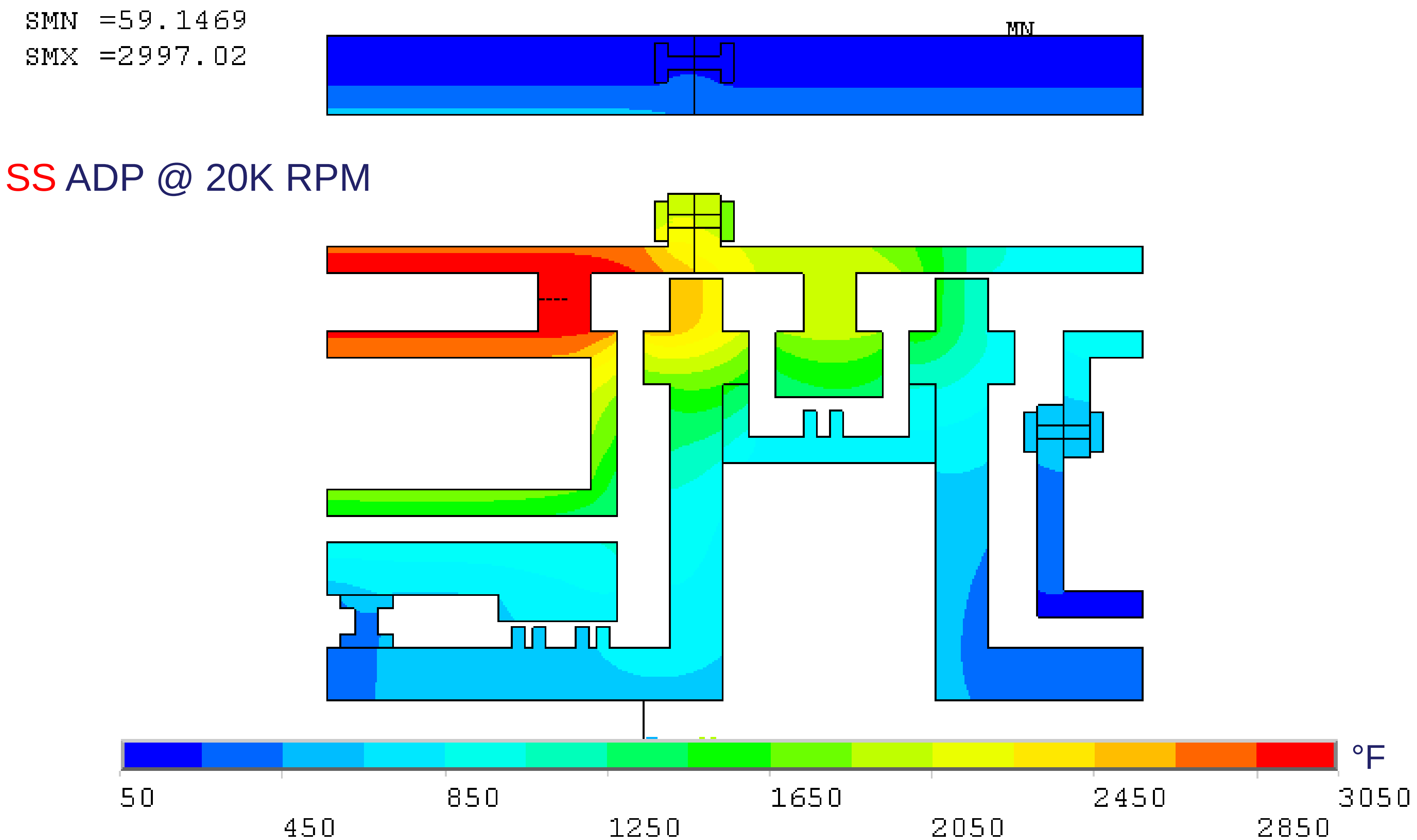
End Transient Accel To 20K RPM



Load Step 3 @ 3629.999 Seconds



Load Step 4 @ 3630 Seconds



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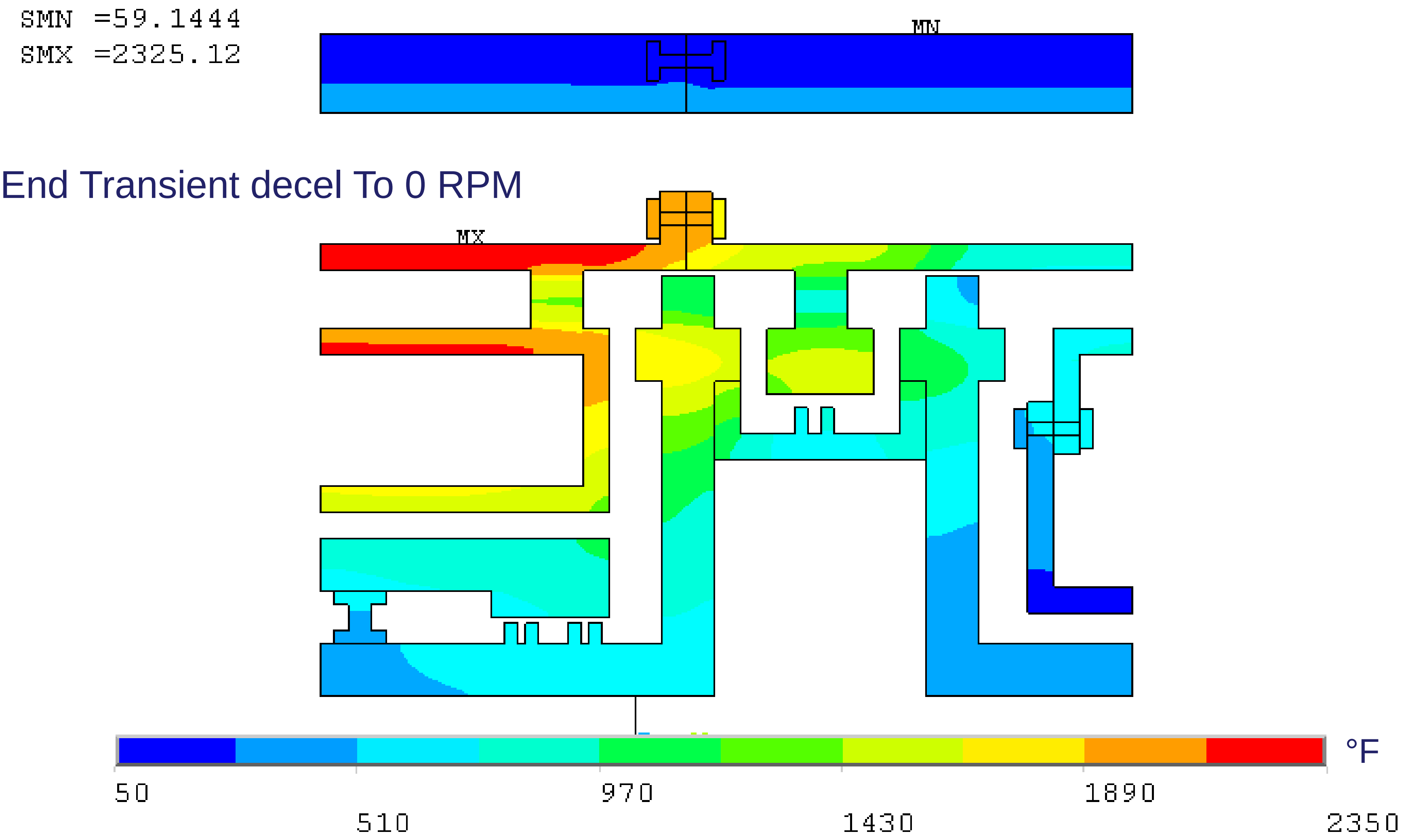
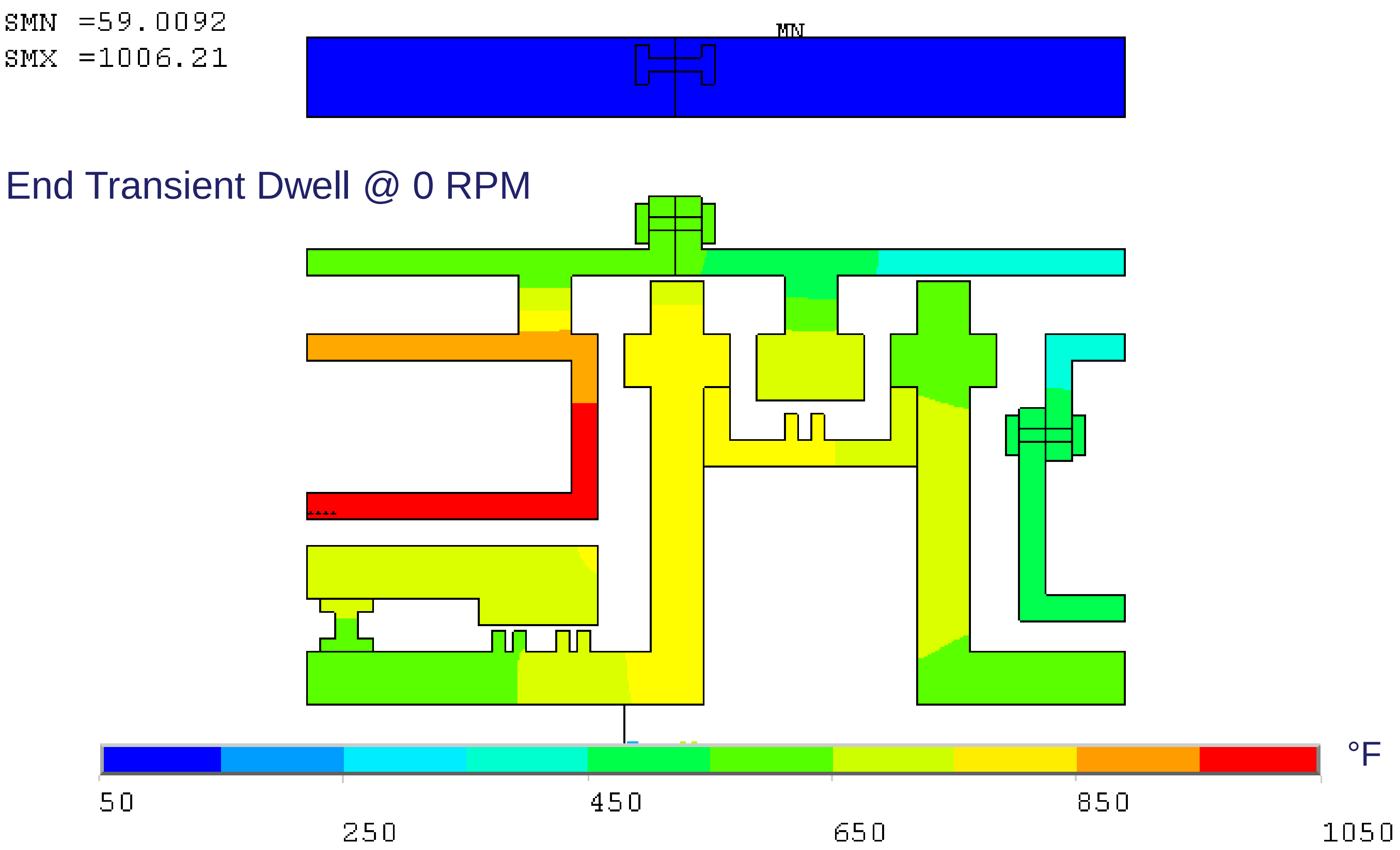
Load Step 5 @ 3660 Seconds

End Transient decel To 0 RPM



Load Step 6 @ 7260 Seconds



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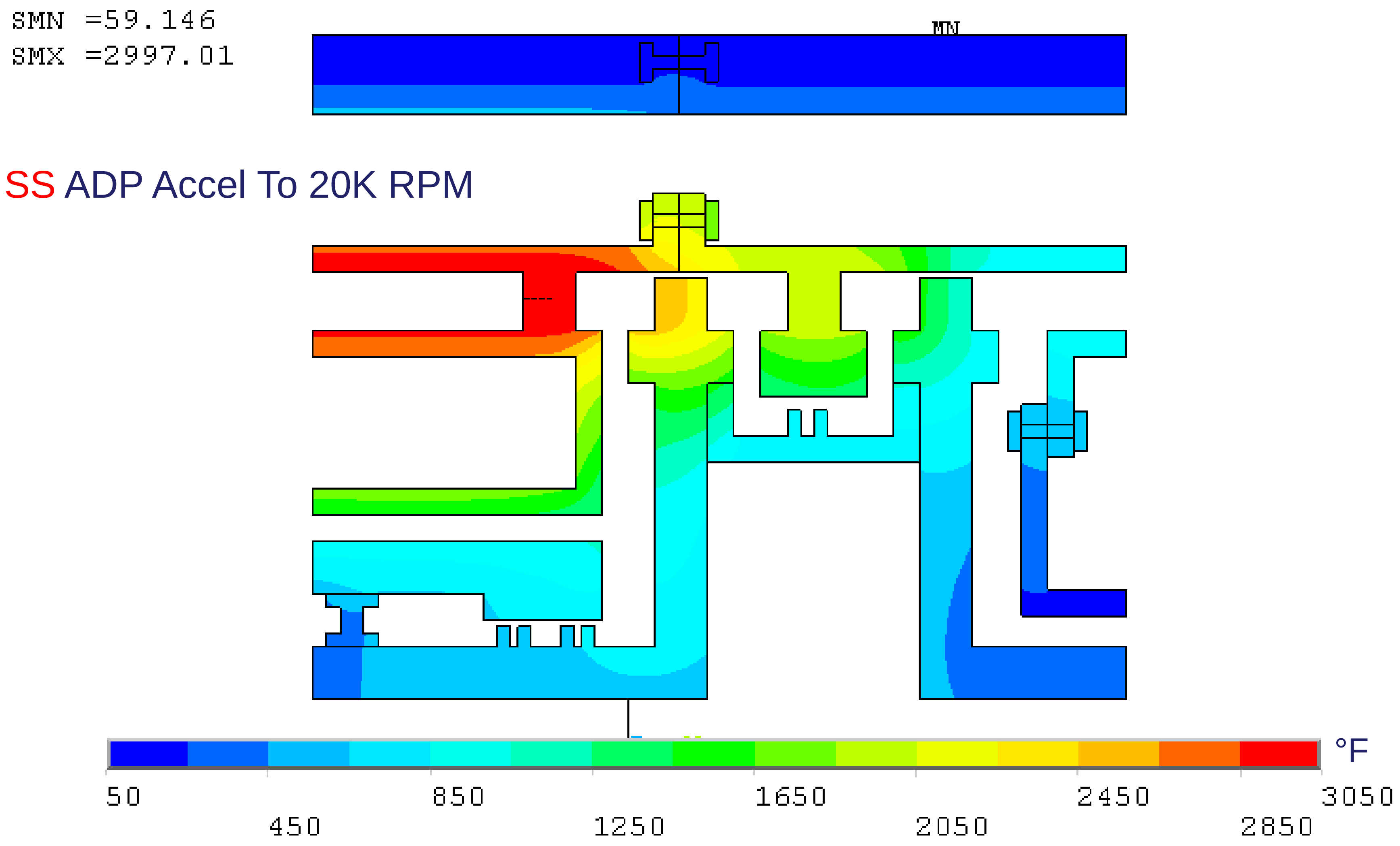
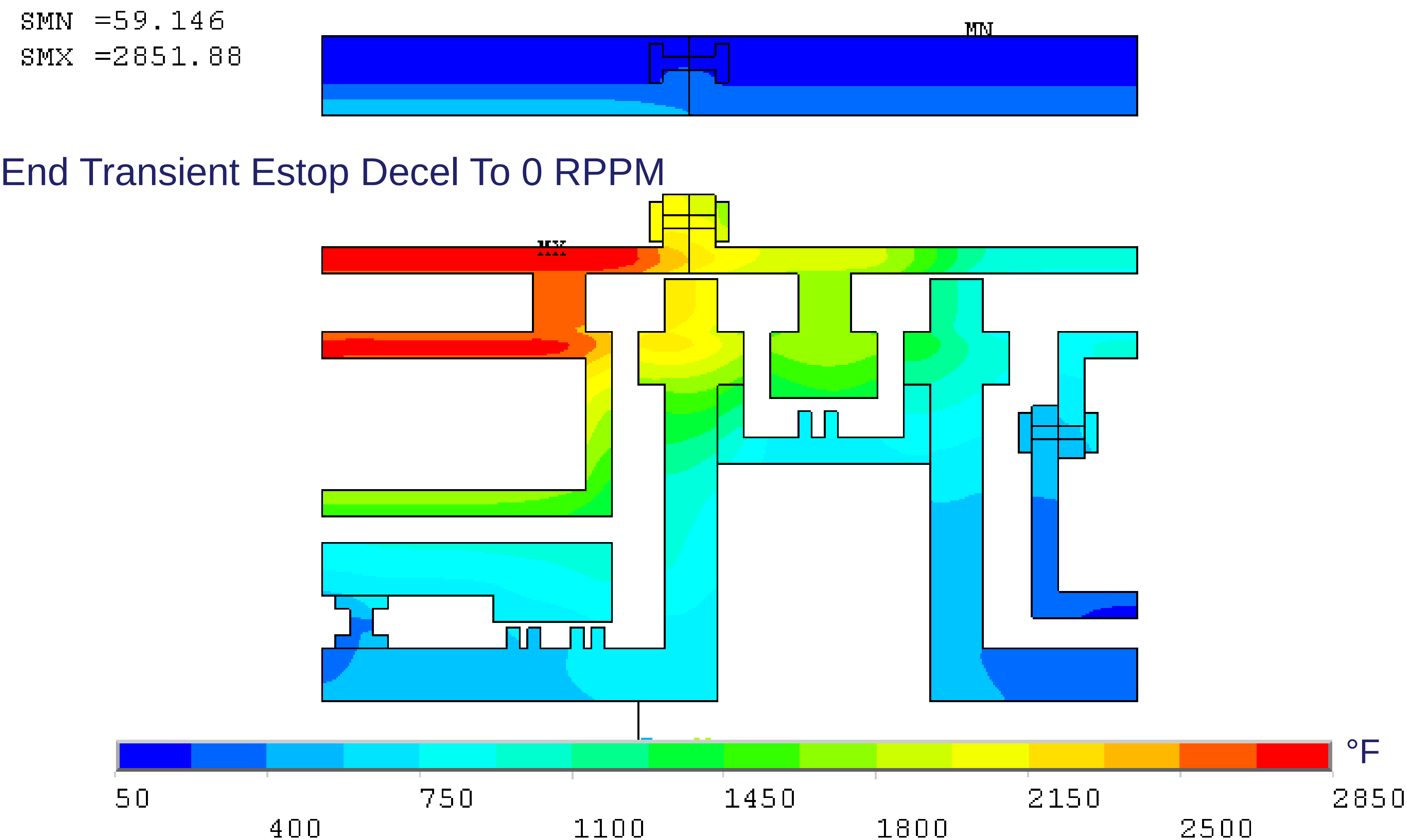
Load Step 7 @ 7261 Seconds

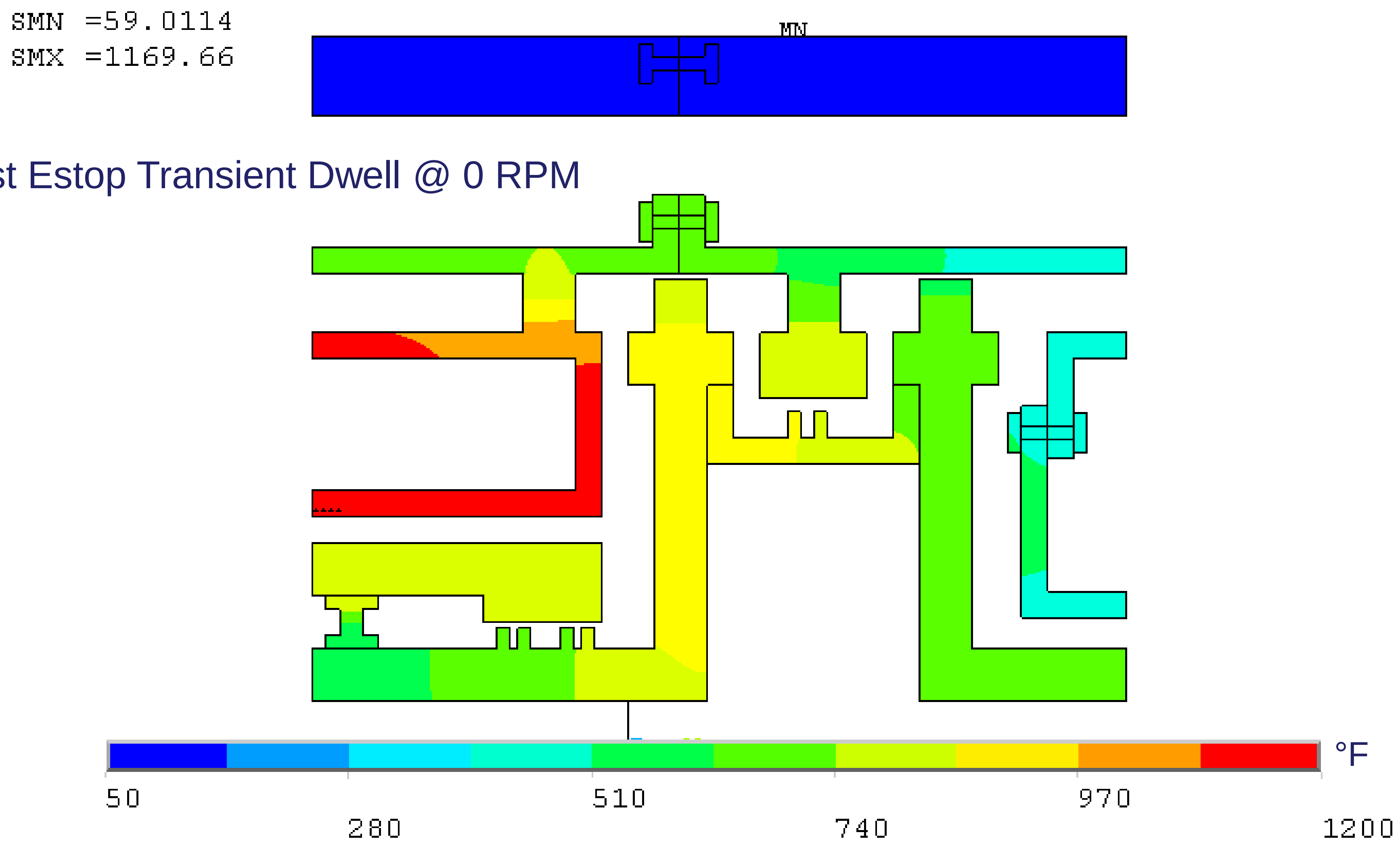


Load Step 8 @ 7264 Seconds

End Transient Estop Decel To 0 RPPM

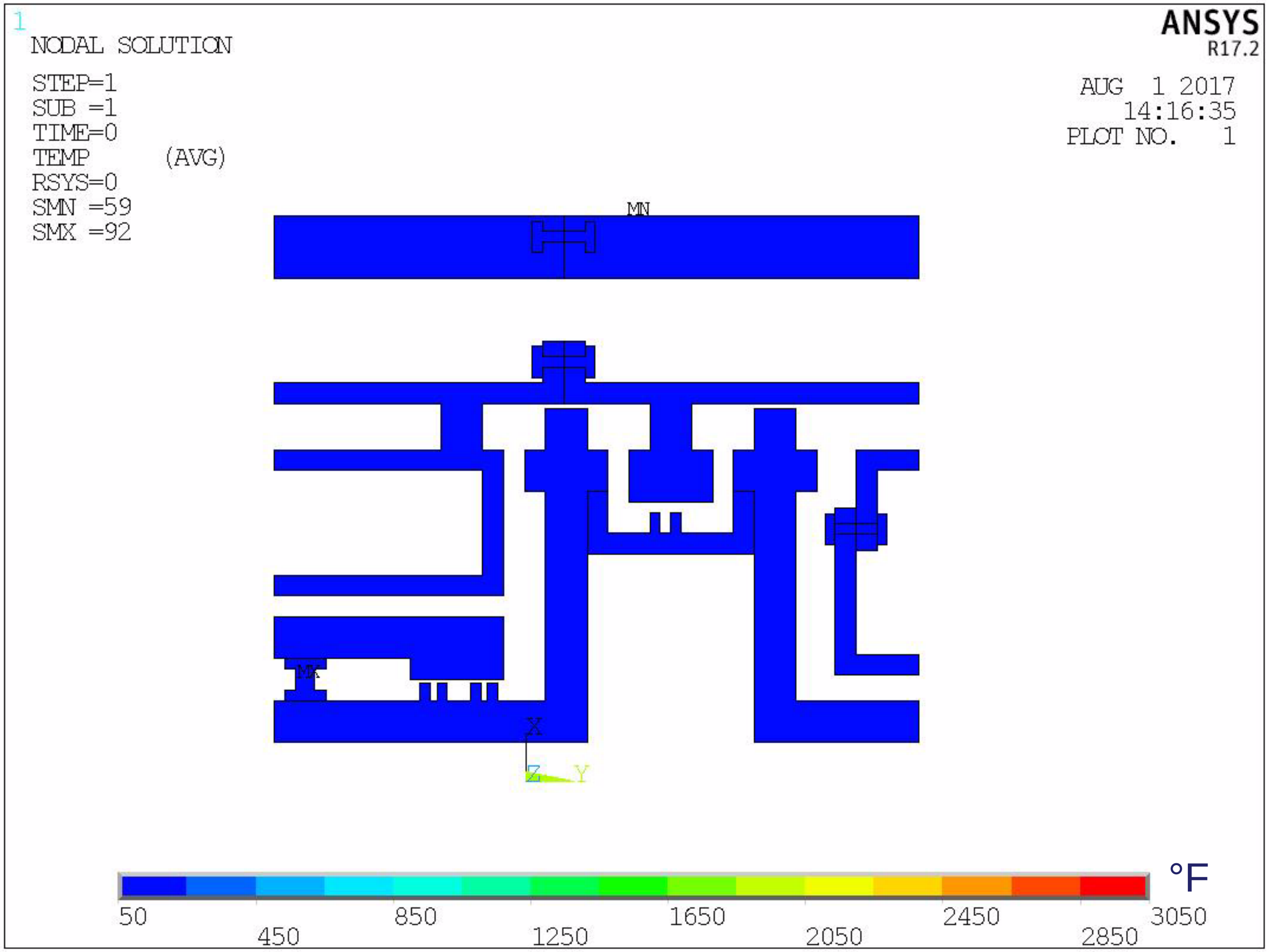


Load Step 9 @ 10864 Seconds



Post Estop Transient Dwell @ 0 RPM

Metal Nodal DOF Temp Up to The 6th Load Step (Temperature Vs. Time animation)



Hand calculations to prove results

1-D SS Hand Calc @ t = 3630 s

(Cold purge air entrance b/w 2nd rotor and right cavity)

Knowns

$h_b := \frac{100}{518400}$ $h_t := \frac{50}{518400}$ $k := 0.0002$ $As_{bottop} := 36.945$ $m_{dot} := \frac{0.15}{386}$ $c_p := 92.69$ $q_{gen} := 0.75$

$r_{topbot} := 2.6$ $L_{topbot} := 1.5$ $As_{topbot} := 2\cdot\pi\cdot r_{topbot}\cdot L_{topbot}$ = -----> $As_{topbot} = 24.504$

$r2 := 2$ $r1 := 1$ $L_{bottop} := 2.94$

$R_{cond\_bot} := \frac{\ln\left(\frac{r2}{r1}\right)}{2\cdot\pi\cdot k\cdot L_{bottop}}$ = -------> $R_{cond\_bot} = 187.615$

$R_{conv\_botmid} := \frac{1}{h_t\cdot As_{bottop}}$ = -------> $R_{conv\_botmid} = 280.633$

$R_{conv\_topmid} := \frac{1}{h_t\cdot As_{topbot}}$ = -------> $R_{conv\_topmid} = 423.107$

Temperatures

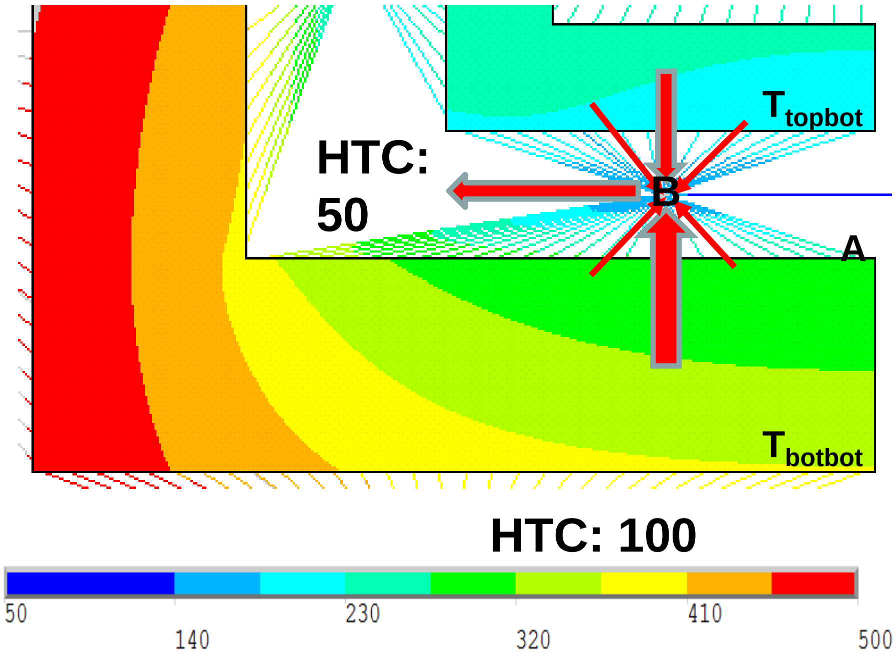
$T_{ini} := 100$ $T_{botbot} := 396.26$ $T_{topbot} := 221.357$

Equ A: $\frac{T_{botbot} - Ta}{R_{cond\_bot}} = \frac{Ta - Tb}{R_{conv\_botmid}}$

Equa B: $q_{gen} + \frac{Ta - Tb}{R_{conv\_botmid}} + \frac{T_{topbot} - Tb}{R_{conv\_topmid}} = m_{dot}\cdot c_p\cdot(Tb - T_{ini})$

$\begin{pmatrix} Taval \\ Tbval \end{pmatrix} := \text{Find}(Ta, Tb)$

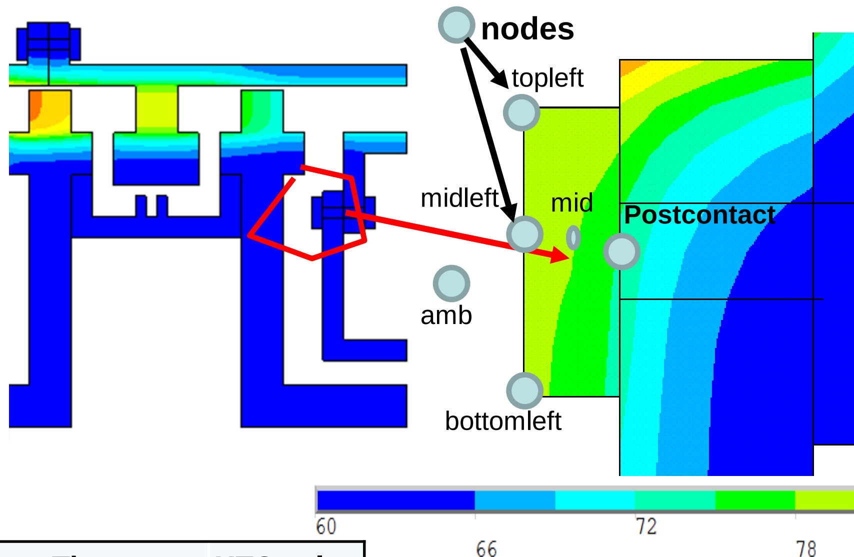
Calculated	Ansys solution	Difference	
Taval = 294.066	AnsTa := 293.324	D1 := Taval − AnsTa	D1 = 0.742
Tbval = 141.204	AnsTb := 142.825	D2 := Tbval − AnsTb	D2 = −1.621



NOTE

ACTUAL HEAT TRANSFER BEHAVES MORE LIKE A 2D PROBLEM SO 1D CALCULATIONS WAS EXPECTED TO BE OFF BY A COUPLE DEGREES EVEN THOUGH ANSWERS CAME QUITE CLOSE

1-D Transient Hand Calc from t = [0.01 to 30] s



Knowns

$h_c := \frac{50}{518400}$ $k_n := 0.0001551$ $th_{ntot} := 5.87$ $diam_n := 0.75$ $th_n := 0.25$

$r_n := 6.095$ $circ := 2 \cdot \pi \cdot r_n$ $Sp := 5 \cdot diam_n$ $N_n := \frac{circ}{Sp}$ $N_n = 10.212$

$As_n := \left(\frac{\pi}{4} \cdot diam_n^{\,2} + \pi \cdot diam_n \cdot th_n\right) \cdot N_n$ $As_n = 10.527$ $V_n := th_n \cdot diam_n \cdot th_{ntot} \rightarrow 1.100625$

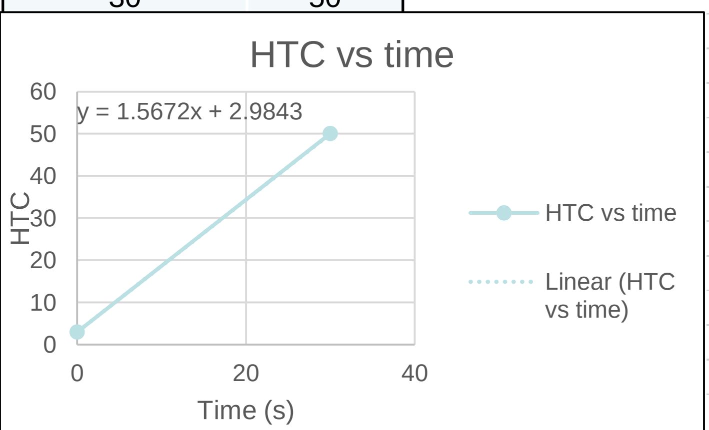
$As_{contact} := \frac{\pi}{4} \cdot diam_n^{\,2} \cdot N_n$ $As_{contact} = 4.512$

$L_{c\_n} := \frac{V_n}{As_n}$ $L_{c\_n} = 0.105$

$Bi_n := \frac{h_c \cdot L_{c\_n}}{k_n}$ $Bi_n = 0.065$

Bi << 1 So lumped assumption is acceptable here

Time	HTC value
0.01	3
30	50



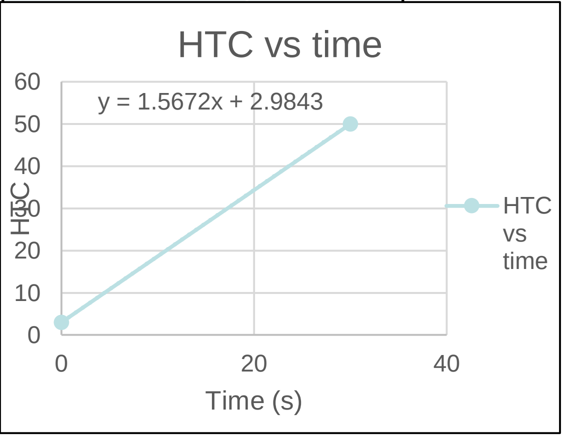
Node Temperature Vs. Time

TIME	topleft	midleft	bottomleft	mid	amb	postcontact
0.010	60.5240697	60.5270201	60.5100175	60.5252189	61.1164382	60.5185899
0.020	60.5235286	60.5264871	60.5100043	60.5246915	33.6913354	60.5152632
0.023	60.5233481	60.5263094	60.5099998	60.5245134	33.934058	60.5142048
0.024	60.523288	60.5262501	60.5099984	60.5244538	34.0149981	60.5138576
0.026	60.5232279	60.5261909	60.5099969	60.524394	34.0957897	60.5135157
0.027	60.5231678	60.5261318	60.5099954	60.524334	34.1764331	60.5131791
0.028	60.5231079	60.5260727	60.509994	60.5242739	34.2569286	60.5128477
0.029	60.5230479	60.5260136	60.5099925	60.5242136	34.3372765	60.5125215
0.030	60.5229881	60.5259546	60.5099911	60.5241533	34.417477	60.5122002
0.031	60.5229284	60.5258957	60.5099897	60.5240928	34.4975304	60.5118839
0.032	60.5228688	60.5258369	60.5099883	60.5240323	34.5774369	60.5115724

1-D Transient Hand Calc from t = [0.01 to 30] s

- T_node_calc shows temperature calculation including contact resistance and contact surface area
- First temperature in T_node_calc is an average of initial temperatures of nodes selected and are part of the bolt nut
- HTC values is parameterized to change linearly b/w load steps

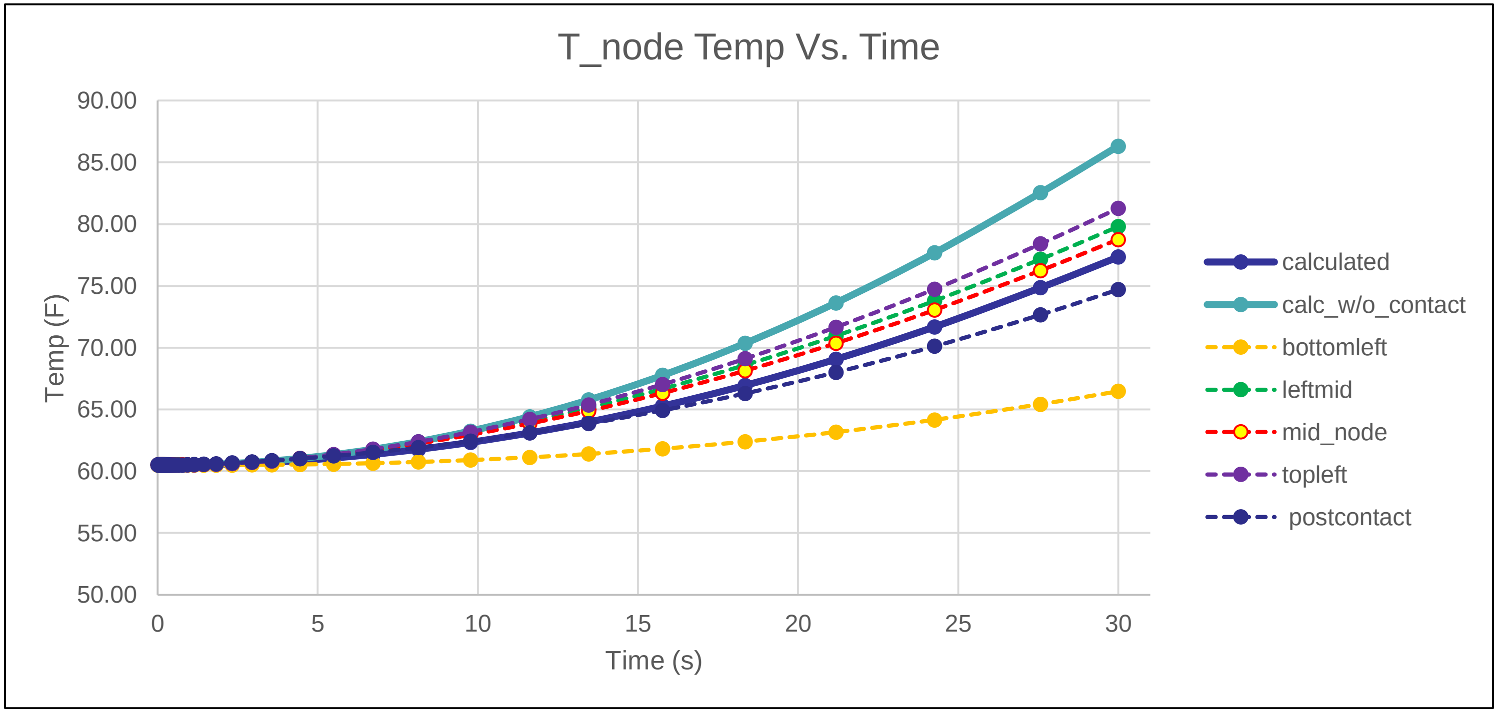
Time	HTC value
0.01	3
30	50



T_infin_eff	htc_1	htc_eff	tau	tau_eff	T_node_calc	T_node_w/o_contact
					60.52158155	
41.73904883	3.015644	2.081599071	522.7593261	530.1154	60.52	6.05E+01
41.90863226	3.020868	2.085154902	521.8553161	529.2114	60.52	60.52089849
41.96518455	3.0226093	2.086340141	521.5546739	528.9108	60.52	60.52084202
42.02163448	3.0243507	2.087525361	521.2543778	528.6105	60.52	60.52078569
42.07798227	3.026092	2.088710562	520.9544274	528.3105	60.52	60.52072951
42.13422809	3.0278333	2.089895744	520.654822	528.0109	60.52	60.52067346
42.19037215	3.0295747	2.091080907	520.3555609	527.7117	60.52	60.52061755
42.2464145	3.031316	2.092266051	520.0566437	527.4127	60.52	60.52056178
96.45433394	21.192932	13.49963767	74.38593272	81.74203	63.10	64.41851564
98.32751952	24.084627	15.15551727	65.45486456	72.81096	63.98	65.77168027
100.6165889	27.702652	17.17158825	56.90632131	64.26242	65.27	67.76500277
103.1702156	31.739374	19.35098878	49.66878178	57.02488	66.95	70.35287449
106.0511023	36.187528	21.67117297	43.56351835	50.91961	69.07	73.6329412
109.3119909	41.011875	24.09619238	38.43901356	45.79511	71.68	77.67178245
113.0263969	46.199207	26.60346033	34.12301072	41.47911	74.86	82.53911358
115.8705097	50.0003	28.37821768	31.52893133	38.88503	77.34	86.31339979

Transient Hand Calc from t = [0.01 to 30] s

- Calculated (dark blue) solid line shows best match to the actual temperatures of the nodes around the bolt nut
- Cal_w/o_contact (turquoise) solid line shows calculated temperature without considering contact resistance which over predicts the actual temperature



Equations used for transient calculations

- $T = T_\infty + (Ti - T_\infty) * e^{-(t/\tau)}$
- $\tau = \frac{\rho * V * cp}{h * As}$
- $T_{eff} = \frac{T_1 * A_1 + T_2 * A_2}{A_1 + A_2}$
- $\frac{1}{U * A_{tot}} = \frac{1}{h_1 * A_1} + \frac{1}{TCC * A_2}$
  - *TCC = thermal contact conductance*
- $\tau_{eff} = \frac{\rho * V * cp}{U * A_{tot}}$

Transient Hand Calc on 1st Vane from t = [0.01 to 30] s

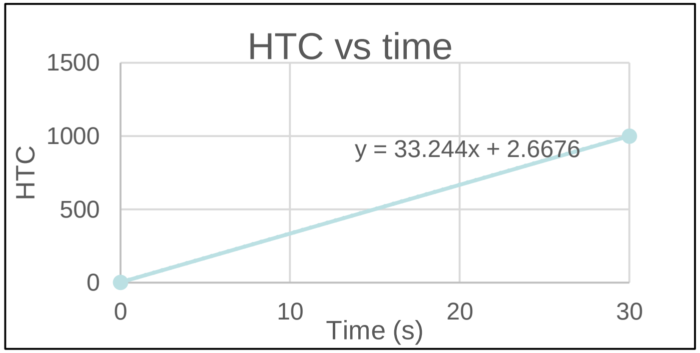
- Ambient temperature, C_p, and HTC would be changing with time
- This means that "τ" has to be updated with time as well
- Temperature-dependent metal and air properties were inputted into ANSYS
- Biot # < 1; Lump capacitance is assumed to see how well calculations match with the software calculations

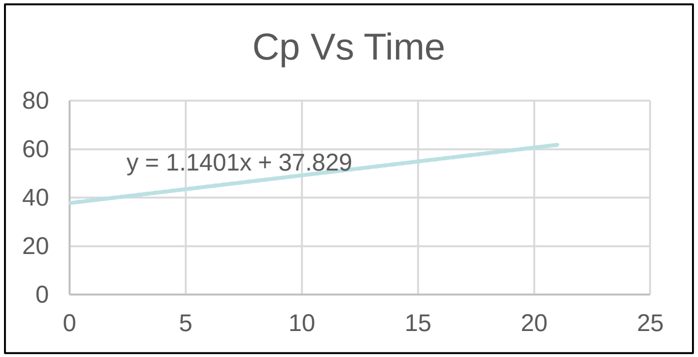
Knowns **Vane 1**

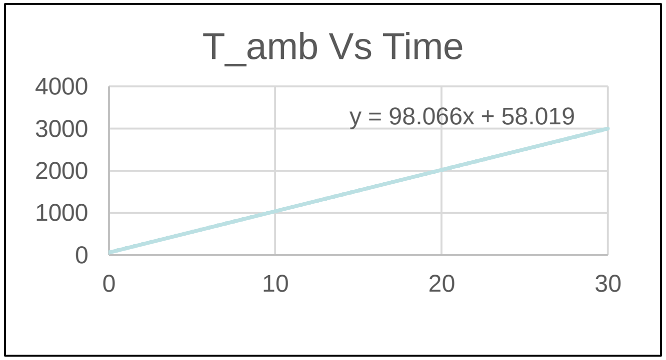
$h_v := \frac{1000}{518400}$ $k := 0.0003194$ $th := 8.14$ $L_v := 1$ $H_v := 1.1$ $N_{foil} := 30$

$As := 2 \cdot N_{foil} \cdot (L_v \cdot H_v) \rightarrow 66.0$ $V_v := L_v \cdot H_v \cdot th \rightarrow 8.954$ $L_c := \frac{V_v}{As}$ $L_c = 0.136$

$Bi_v := \frac{h_v \cdot L_c}{k} \rightarrow .81935715371671678638$







Transient Hand Calc on 1st Vane from t = [0.01 to 30] s

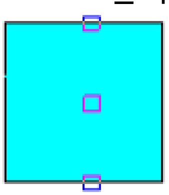
Knowns		
Height	1.1	in
Width	1	in
th_tot	8.14	in
Volume =	8.954	in^3
density	0.00076863	sling/in^3
mass	0.00688231	sling
As_tot =	66	in^2
N_airfoils	30	
th_above/b	0.5	in
Ac_vane1	8.14	in^2
htc_unit_co	518400	

TIME			
0	Vane1_top	Vane1_mid	Vane1_low
0.01	59.6536739	60.5944067	61.4843542
0.02	59.6537833	60.5944201	61.4844516
0.023333333	59.6538333	60.5944263	61.4844965
0.024444444	59.6538516	60.5944286	61.4845129
0.025555556	59.6538714	60.594431	61.4845307
↓	↓	↓	↓
26.931972	1867.92207	2253.61074	1888.8352
27.931972	1965.24696	2367.23735	1987.77592
28.931972	2064.82099	2480.5479	2087.66258
29.465986	2118.26367	2540.92888	2141.18748
30	2171.8766	2601.16667	2194.86674

Nodes evaluated

Vane1_top

Vane1_mid



Vane1_low

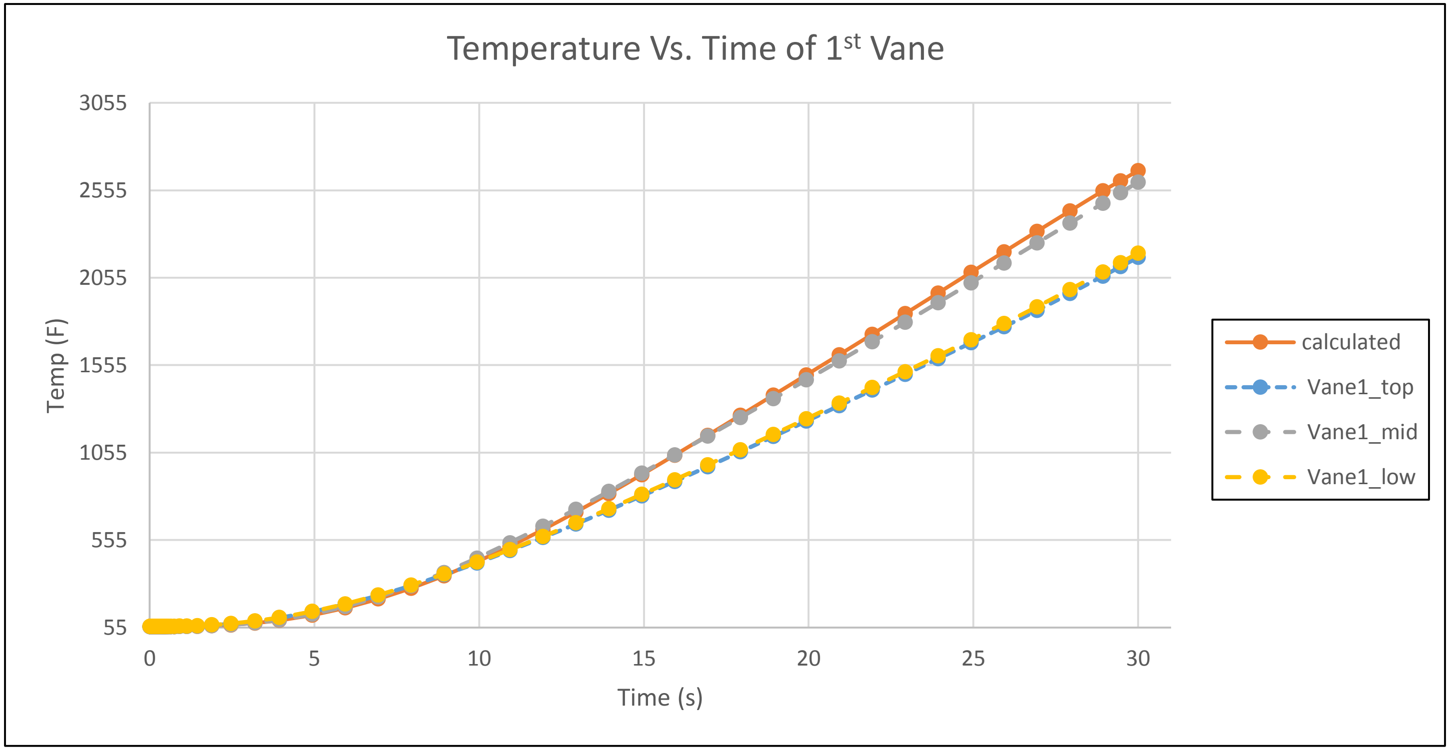
Min Temp of 59°F
HTC of 3 Btu/hr/ft^2/°F

ADP Temp of 3000°F
HTC of 1000 Btu/hr/ft^2/°F

				T_node_calc
amb	htc_1	cp	tau	60.57747827
58.99966	3.00004	37.840401	681.84265	60.57745513
59.98032	3.33248	37.851802	614.008646	60.5774454
60.30720667	3.4432933	37.85560233	594.3080565	60.57744389
60.41616889	3.4802311	37.85686911	588.0199855	60.57744358
↓	↓	↓	↓	↓
2797.195766	931.23808	61.77	3.585686817	2436.299824
2895.261766	964.48208	61.77	3.462094502	2551.439519
2947.630383	982.23484	61.77	3.399521138	2609.033247
2999.999	999.9876	61.77	3.339169502	2666.814707

Transient Hand Calc on 1st Vane from t = [0.01 to 30] s

- Calculated temperature followed same trend as the middle node temp of the vane but reached higher temperature at the end of the load step



ANSYS Error Encounter

- 1D SS hand calculation was attempted within the bleed section of the model, but calculations did not match ANSYS
- Too few fluid nodes were utilized to capture the large temperature gradient in that area
- More fluid nodes would better capture large temperature gradients
- This was taken into account, and the project continued as-is
- Comparison of ANSYS versions is still valid
- For the purpose of checking SS 1D hand calculations without permanently changing the initial BCs placed on the model; the bleed section was temporarily modified where…
  - Radiation was omitted from the outer casing
  - Inlet flow temperature to the flow path was reduced to 1000°F
  - Top section exposed to ambient was modeled as adiabatic
  - flow rate was increased from 0.03 lbm/s to 0.3 lbm/s
- Calculations proved to be within a couple of degrees from ANSYS thermal output

1D SS Bleed Section Hand Calc @ t = 3630 s

Knowns

$r_2 := 12.6$ $r_1 := 12.1$ $k := 0.0002546$ $L := 6.44$ $m_{dot} := \frac{0.3}{386}$ $c_p := 95$

$h_{bleed} := \frac{30}{518400}$ $h_{amb} := \frac{0.00001}{518400}$ $h_{flow} := \frac{1000}{518400}$ $r_{2bot} := 9.6$ $r_{1bot} := 9.1$

$As_{conv\_bot} := 388.508$ $As_{conv\_hg} := 369.118$ $As_{conv\_top} := 527.696$ $As_{conv\_amb} := 509.917$

$$R_{conv\_amb} := \frac{1}{h_{amb} \cdot As_{conv\_amb}} \qquad R_{cond\_top} := \frac{\ln\left(\frac{r_2}{r_1}\right)}{2 \cdot \pi \cdot k \cdot L} \qquad R_{conv\_top} := \frac{1}{h_{bleed} \cdot As_{conv\_top}}$$

$$R_{conv\_bot} := \frac{1}{h_{bleed} \cdot As_{conv\_bot}} \qquad R_{cond\_bot} := \frac{\ln\left(\frac{r_{2bot}}{r_{1bot}}\right)}{2 \cdot \pi \cdot k \cdot L} \qquad R_{conv\_hg} := \frac{1}{h_{flow} \cdot As_{conv\_hg}}$$

$R_{cond\_top} = 3.930$ $R_{conv\_amb} = 101663604.077$ $R_{conv\_top} = 32.746$

$R_{cond\_bot} = 5.192$ $R_{conv\_hg} = 1.404$ $R_{conv\_bot} = 44.478$

Temperatures

$T_{ini} := 450$ $T_g := 1000$ $T_{amb} := 59$

5 equations 5 unknowns

Equ A: $$\frac{T_g - Ta}{R_{conv\_hg}} = \frac{Ta - Tb}{R_{cond\_bot}}$$

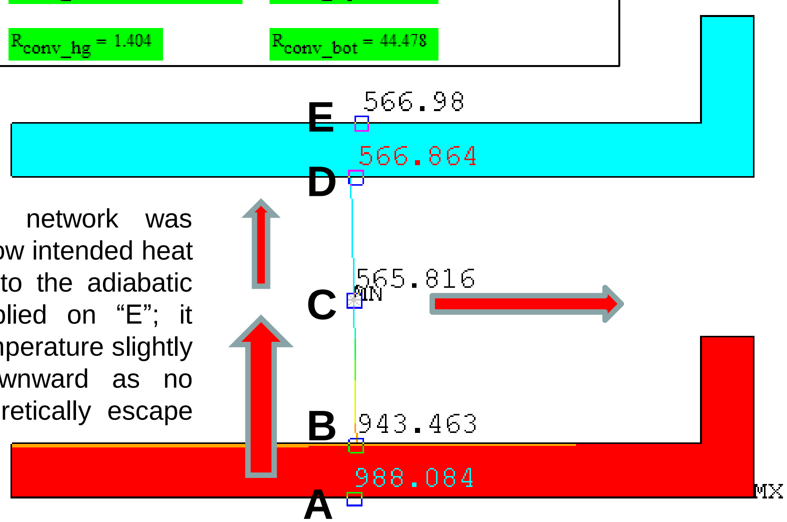
Equ B: $$\frac{Ta - Tb}{R_{cond\_bot}} = \frac{Tb - Tc}{R_{conv\_bot}}$$

Equ C: $$\frac{Tb - Tc}{R_{conv\_bot}} = \frac{Tc - Td}{R_{conv\_top}} + m_{dot} \cdot c_p \cdot (Tc - T_{ini})$$

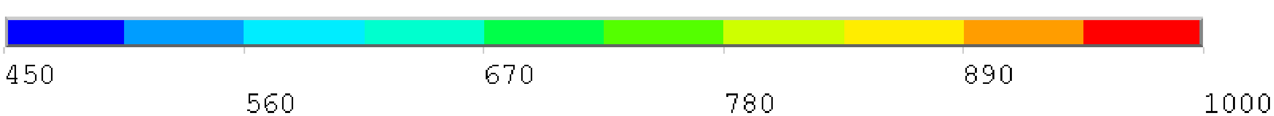
Equ D: $$\frac{Tc - Td}{R_{conv\_top}} = \frac{Td - Te}{R_{cond\_top}}$$

Equ E: $$\frac{Td - Te}{R_{cond\_top}} = \frac{Te - T_{amb}}{R_{conv\_amb}}$$

Calculated Values	Ansys Values
Teval = 565.280	Te = 566.98
Tdval = 565.280	Td = 566.864
Tcval = 565.279	Tc = 565.816
Tbval = 943.854	Tb = 943.463
Taval = 988.046	Ta = 988.084

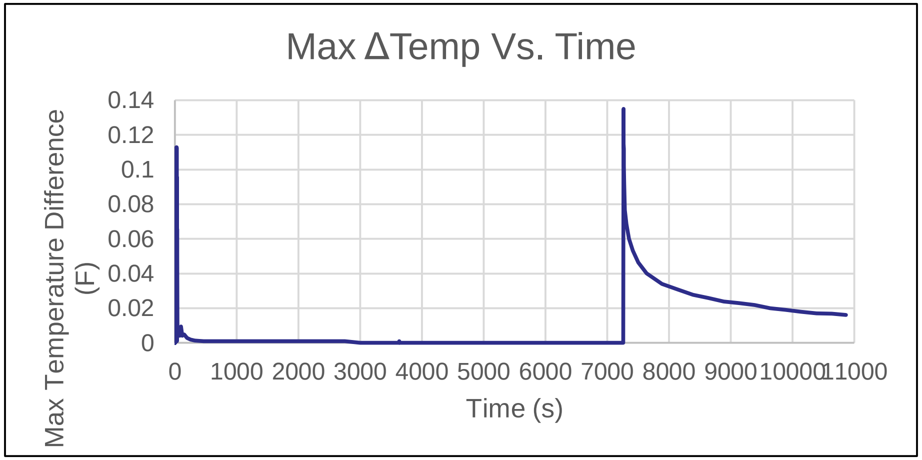


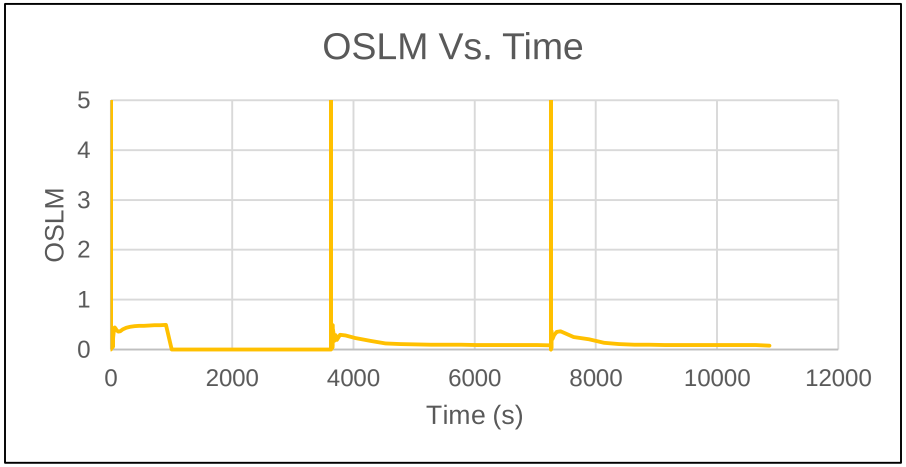
NOTE Heat network was modeled to show intended heat flow, but due to the adiabatic conditions applied on “E”; it seems that temperature slightly decreases downward as no heat can theoretically escape from “E”



Post Processing Results

- A 2nd macro was created to gather all temperatures of every node in the model at all time steps creating a 21,067 x 387 array
- Temperature data is gathered for both ANSYS versions 14.5 and 17.2
- A 3rd macro is utilized to calculate maximum ΔTemp and to output corresponding node and time at which it occurs
- Maximum ΔTemp = 0.135 °F
- Oscillation limit generally remained < 0.5 most of the time
- Low numbers represent better stability of the output results





Conclusion

- Verification test for 2D model was deemed successful
  - Max ΔTemp = 0.135 °F < 1 °F
  - OSLM remained < 1 for most times
  - OSLM > 1 for longest duration < 0.1 seconds
- Future verifications should be easy to do by running all 3 Macros to the same model of future ANSYS versions

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