



Quadratic Control Volumes for Thermal Analysis – Verification, Benefits, and Usage

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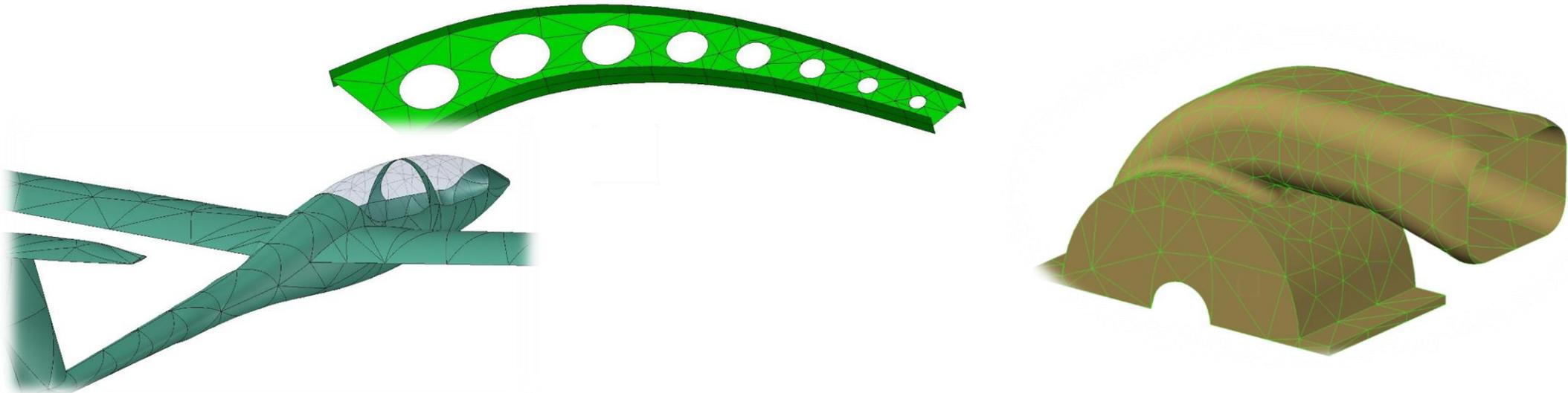
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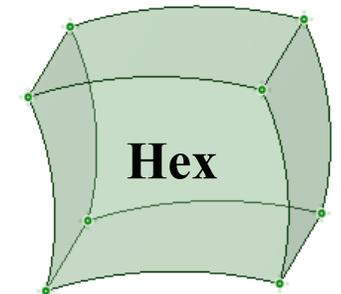
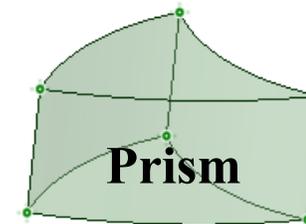
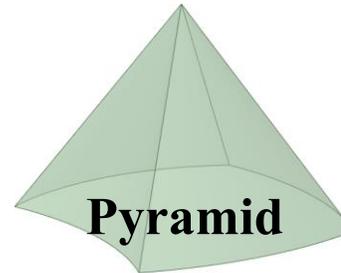
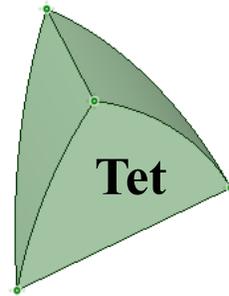
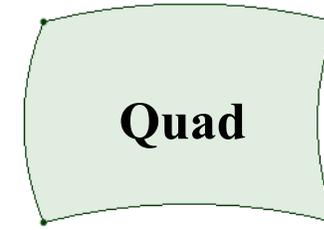
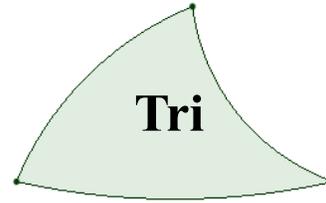
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What are Quadratic Control Volume Elements

- Second-order geometric shape
 - Accurate approximation of curved geometry area and volume at low resolution
- Second-order temperature approximation
 - Mid-side nodes are included in the thermal solution
 - Improved temperature solutions when temperatures have a non-linear distribution
 - Improved postprocessing with non-linear interpolation of results
- Quadratic control volumes are generated with TD Direct in Ansys Thermal Desktop
 - Currently available as a Beta feature introduced in Version 2023 R2



- Thin shell elements
 - Triangular (Tri)
 - Six nodes
 - Three edges
 - Quadrilateral (Quad)
 - Eight nodes
 - Four edges
- Solid elements
 - Tetrahedral (Tet)
 - Ten nodes
 - Four edges
 - Four faces
 - Pyramid
 - Thirteen nodes
 - Eight edges
 - Five faces
 - Prism
 - Twelve nodes
 - Nine edges
 - Five faces
 - Hexahedral (Hex)
 - Twenty nodes
 - Twelve edges
 - Six faces





Discretization Options in Ansys Thermal Desktop



- Finite difference
 - Predefined shapes using finite difference conductance approximations
 - Volume and surface area are independent of resolution
 - Linear thermal solution
- Linear finite elements
 - Galerkin or control volume options
 - Volume and surface area are dependent on resolution for curved geometry
 - Linear thermal solution (vertex nodes only)
- Curved Control Volume
 - Volume and surface area independent of resolution for second-order shapes
 - Linear thermal solution (vertex nodes only)
- Quadratic Control Volume
 - Volume and surface area independent of resolution for second-order shapes
 - Second-order thermal solution (vertex and mid-side nodes)



Testing

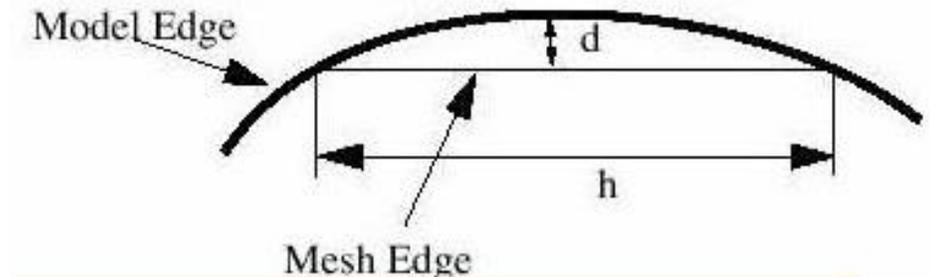


Test Categories

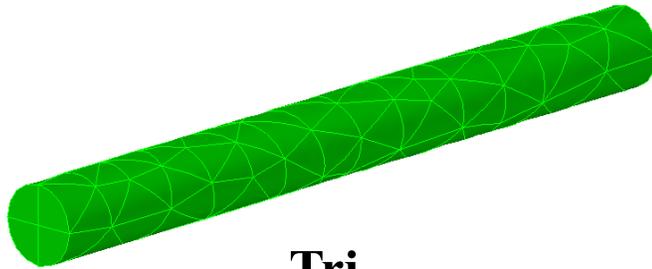


- Geometry
 - Area: Compare thin shell element area to geometry area
 - Volume: Compare solid element volume to geometry volume
 - By similarity to curved control volumes
- Radiation
 - Compare black-body exchange factor to known configurations
 - By similarity to curved control volumes
- Thermal
 - Compare temperature solution to known conductance solution
 - Evaluate using range-based error
 - $\%error_{range} = \left| \frac{Target - Result}{Range} \right|$
 - Range is the range of temperatures based on boundary conditions
 - Unit-independent
 - Traditional percent error divides by the target value
 - When target is value is 0°C, %error is undefined
 - Unit-dependent

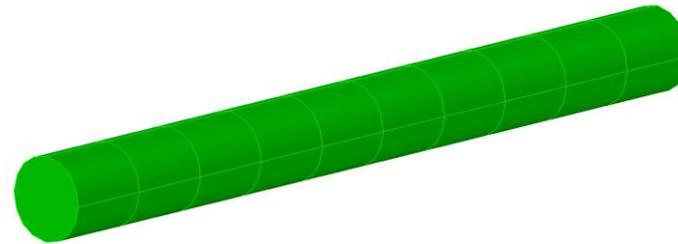
- Keep models simple
 - Maintain focus on the elements
- Test all mesh types that fit a particular problem
- Use the coarsest mesh possible
 - Initial global mesh default values
 - Relative mesh size = 0.99
 - Curvature refinement: Maximum deviation/chord length (d/h) = 0.5
 - Swept mesh used for prism and hex meshes
 - If solution error is large, decrease relative mesh size
 - Formal grid convergence studies were not conducted



- Based on geometry of NAFEMS Thermal Test 3
 - Davies, Fenner, & Lewis, 1993
 - Area of thin shell elements
 - Circle
 - Cylinder



Tri

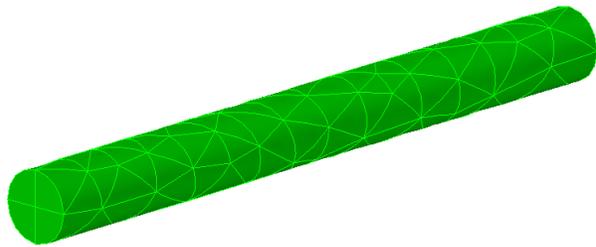


Quad

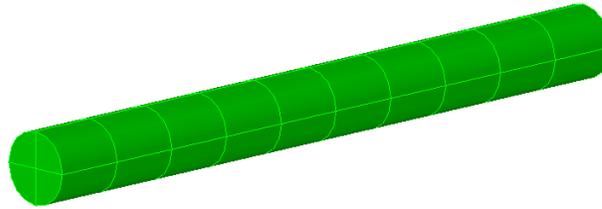
Test	Element Type	Elements	Target (m ²)	Result (m ²)	Error
Cylinder	Quad	40	0.003142	0.003125	0.54%
	Tri	118	0.003142	0.003125	0.53%
Disk	Quad	1	7.85E-05	7.76E-05	1.18%
	Tri	4	7.85E-05	7.76E-05	1.18%

Bell & Panczak (2016)

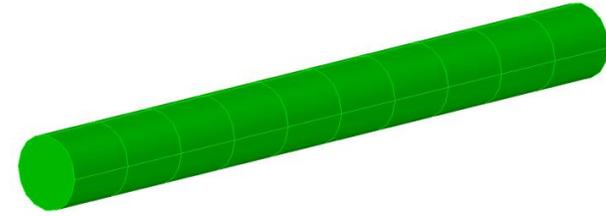
- Based on geometry of NAFEMS Thermal Test 3
 - Davies, Fenner, & Lewis, 1993, p. 107
 - Volume of solid elements
 - Cylinder



Tet



Prism



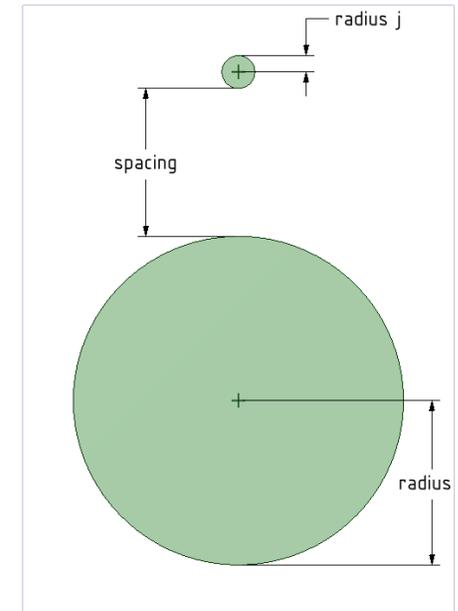
Hex

Test	Element Type	Elements	Target (m ³)	Result(m ³)	Error
Cylinder	Hex	10	7.85E-06	7.37E-06	6.12%
	Prism	40	7.85E-06	7.37E-06	6.12%
	Tet	177	7.85E-06	7.44E-06	5.23%

Bell & Panczak (2016)

- Parallel infinite cylinders

- Howell, *A Catalog of Radiation Heat Transfer Configuration Factors*, 2018
- Black-body view factor calculated from relationships provided in standard texts
- 1 million rays per node
 - Each cylinder represented by 1 node
- Tessellated method
 - Subdivides curved elements into facets
 - Setting 24 max facets per full circle
 - Reasonable for gray-body analysis
- Exact method
 - Shoots rays from the curved element surface
 - Best used for specular reflection and transmission

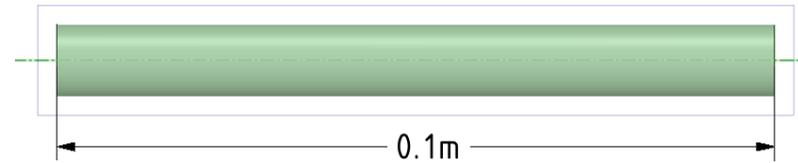


Radiation Test Results

Radius i (m)	Radius j (m)	Spacing (m)	Fij	Calculation Method	Element Type	Fij calculated	Error
0.5	0.5	0.01	0.1788	Tesselated	Tri	0.1771	0.96%
					Quad	0.1770	1.01%
				Exact	Tri	0.1781	0.37%
					Quad	0.1777	0.60%
1	0.1	0.9	0.0167	Tesselated	Tri	0.0166	0.25%
					Quad	0.0165	0.78%
				Exact	Tri	0.0166	0.59%
					Quad	0.0166	0.68%
0.1	1	0.9	0.1668	Tesselated	Tri	0.1663	0.30%
					Quad	0.1663	0.26%
				Exact	Tri	0.1668	0.00%
					Quad	0.1662	0.33%
0.5	0.5	9	0.0159	Tesselated	Tri	0.0159	0.32%
					Quad	0.0159	0.14%
				Exact	Tri	0.0163	-2.53%
					Quad	0.0159	0.49%

Bell & Panczak (2016)

- Test description
 - Davies, Fenner, & Lewis, 1993
 - Transient, 1-D, conductive heat transfer
 - Initial temperature 0°C
 - $T = 0^\circ\text{C}$ at $x = 0$ m
 - $T = 100 \sin\left(\frac{\pi t}{40}\right)^\circ\text{C}$ at $x = 0.1$ m
 - Target value
 - 36.60°C at $x = 0.08$ m at 32 secs

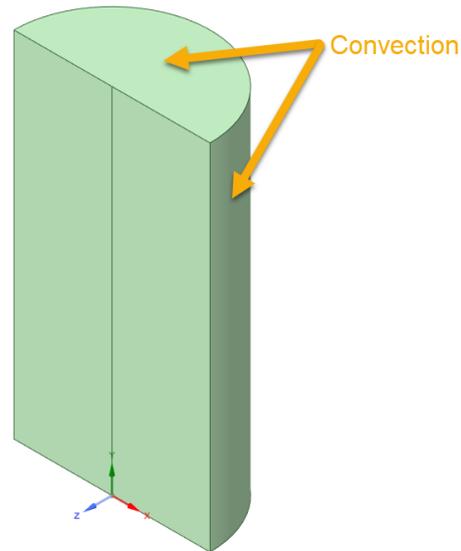


Test	Nodes	Elements	Target (°C)	Results (°C)	Min Temp	Max Temp	Error (Range)
Hex	139	20	36.6	36.0	-100	100	0.30%
Prism	193	40	36.6	36.0	-100	100	0.30%
Tet	579	290	36.6	36.9	-100	100	0.15%



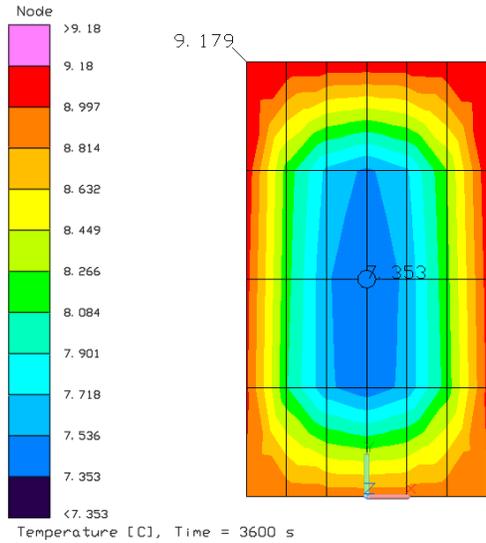
Quadratic Control Volumes In Use

- Small and simple model
 - Natural convection
 - Transient solution

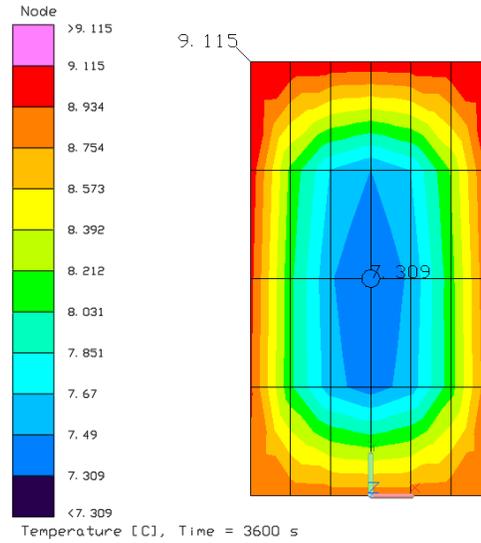


- Results
 - Mass
 - Curved and Quadratic are consistent regardless of model size
 - Linear elements are dependent on model size
 - Solution time
 - Dependent on nodes and conductors

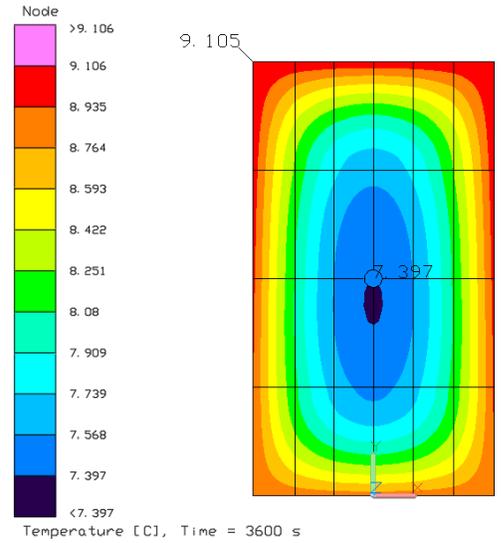
Element Type	Nodes	Elements	Conductors	Mass	Solution time (sec)
Linear	86	166	759	0.238	0.73
Linear - fine	369	768	3504	0.243	0.91
Curved Control Volume	86	176	1198	0.246	0.74
Quadratic Control Volume	329	176	11533	0.246	1.03
Quadratic Control Volume – coarse	64	30	1831	0.246	0.73



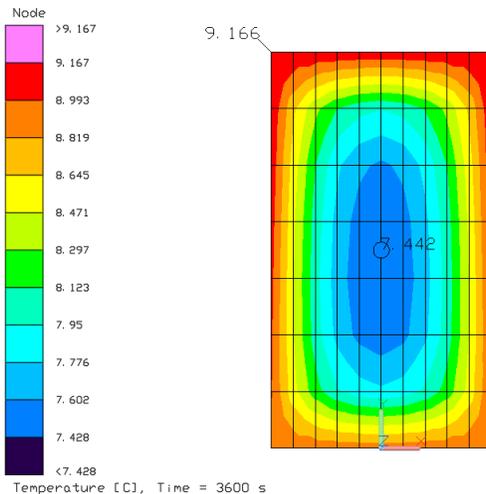
Linear



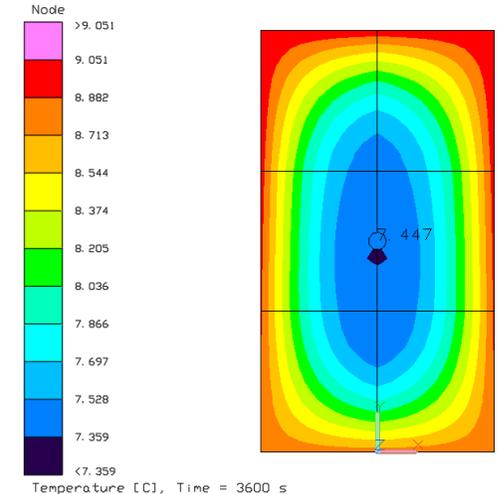
Curved Control Volume



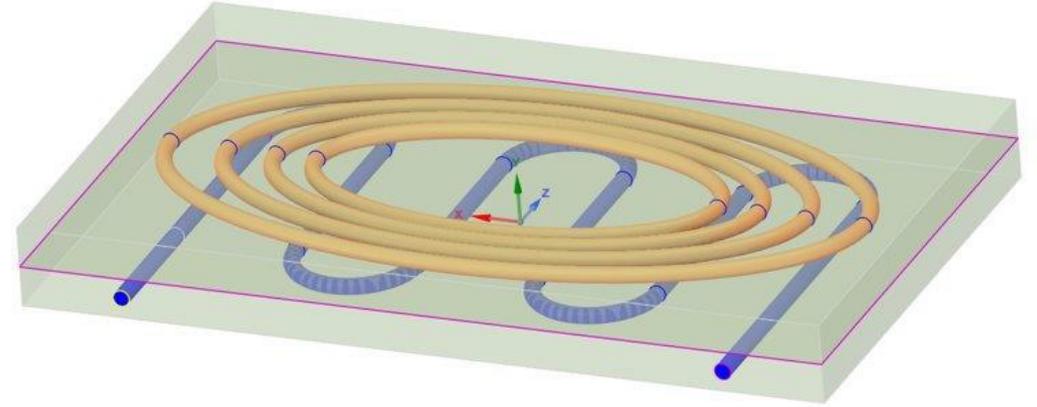
Quadratic Control Volume



- Linear elements require higher resolution to capture solution contours
- Quadratic elements maintain contours at lower resolution
- Quadratic elements retain the geometric advantages of curved elements with added solution accuracy



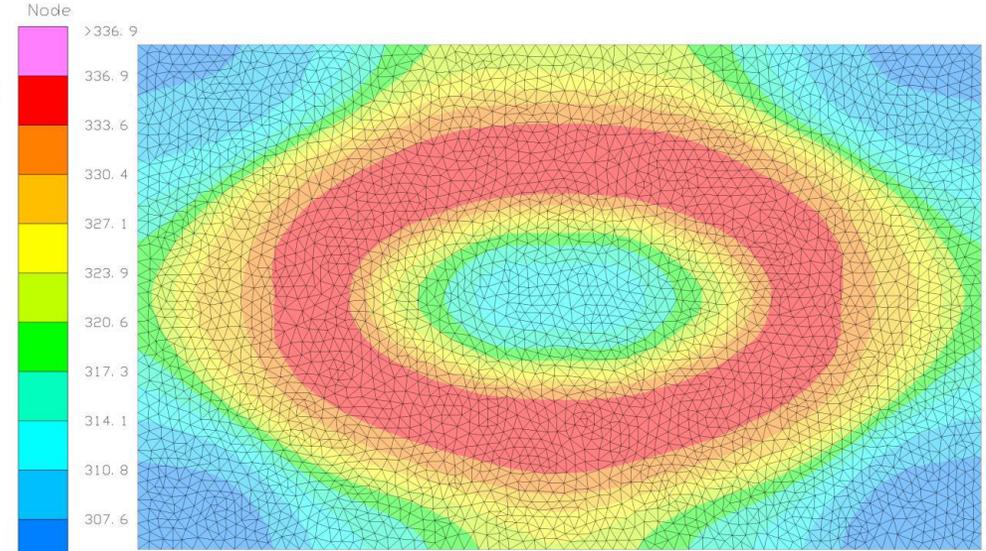
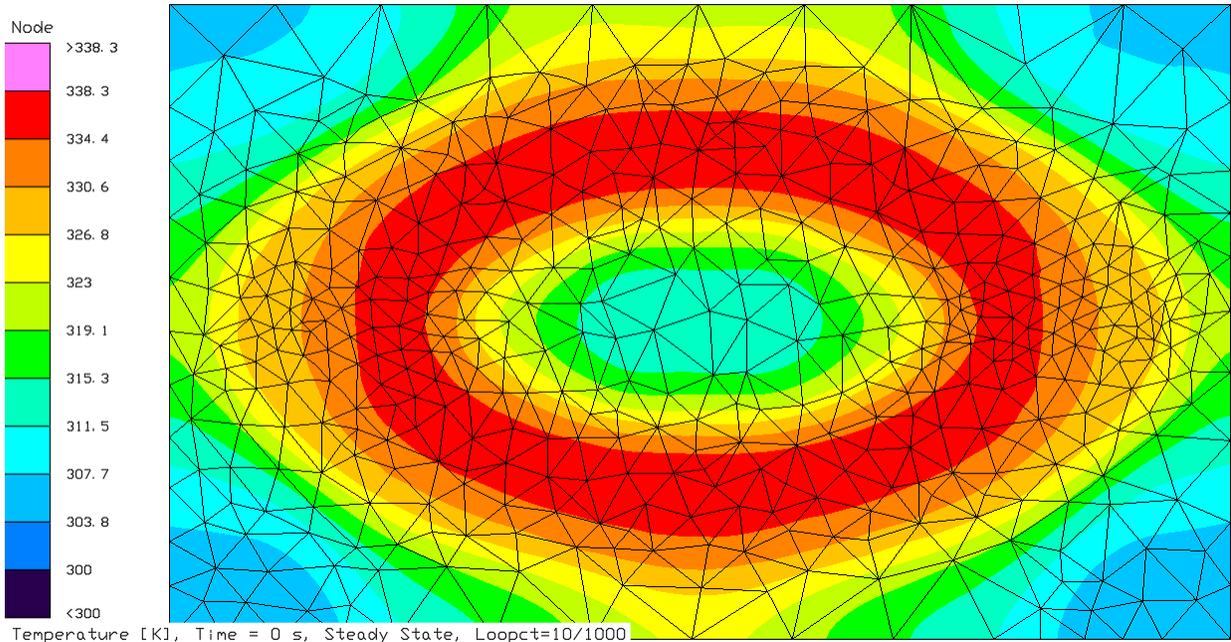
- Complex model
 - Heating coils
 - Liquid cooling
- Meshing Controls
 - 0.2 relative mesh size
 - 0.1 curve refinement
 - Adjust for similar results and similar solution time



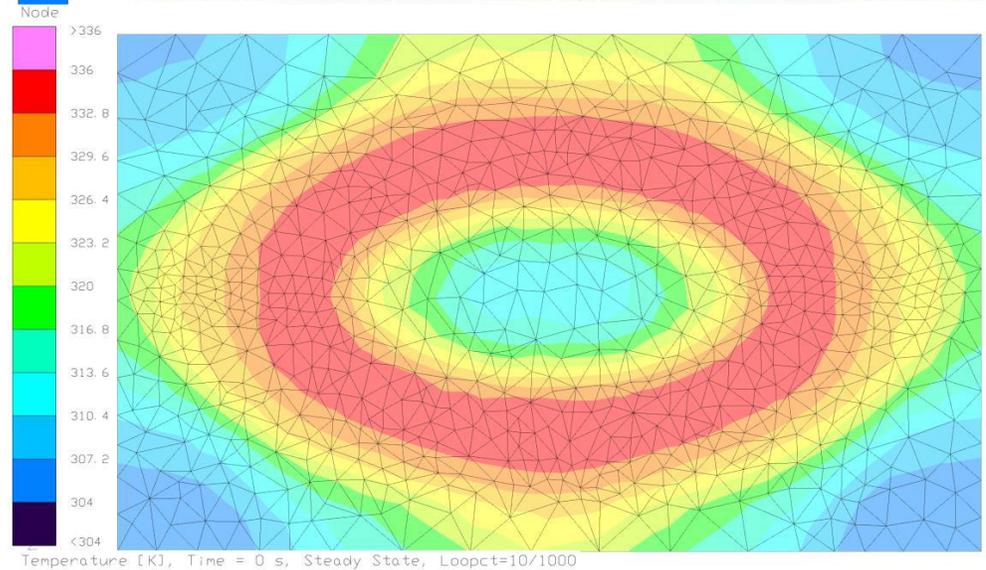
Element type	Mesh time	Solution time	Average Temperature (K)			
			Top surface	Coil wall	Channel temp	Bottom surface
Quadratic Control Volume	1 min	27 min	323.4	334.7	301.1	310.4
Curved Control Volume – 0.015 relative mesh size	6 min	39 min	323.3	334.5	301	310.5
Curved Control Volume – 0.085 relative mesh size	3.5 min	25 min	322.7	333.5	301	310

Similar results

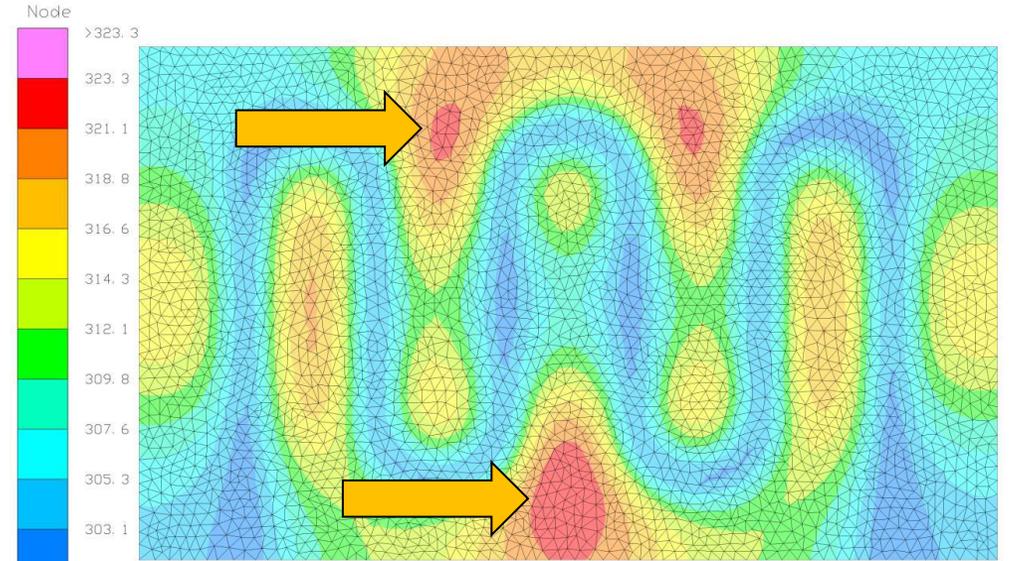
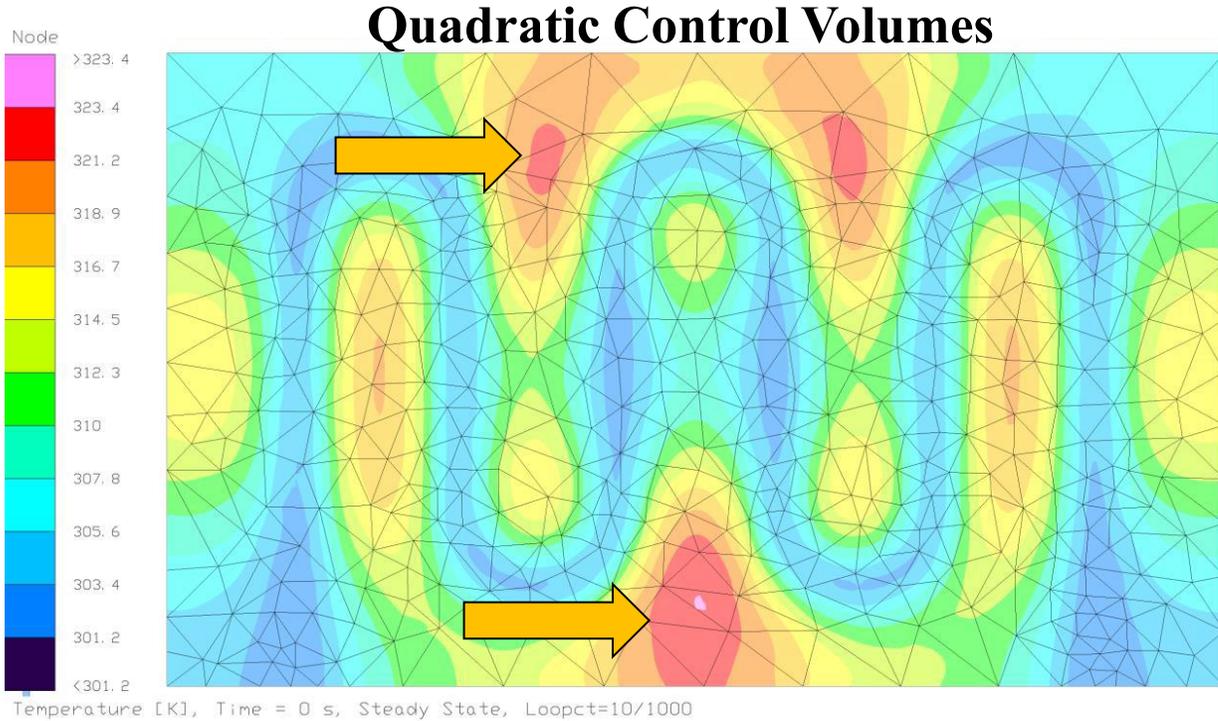
Quadratic Control Volumes



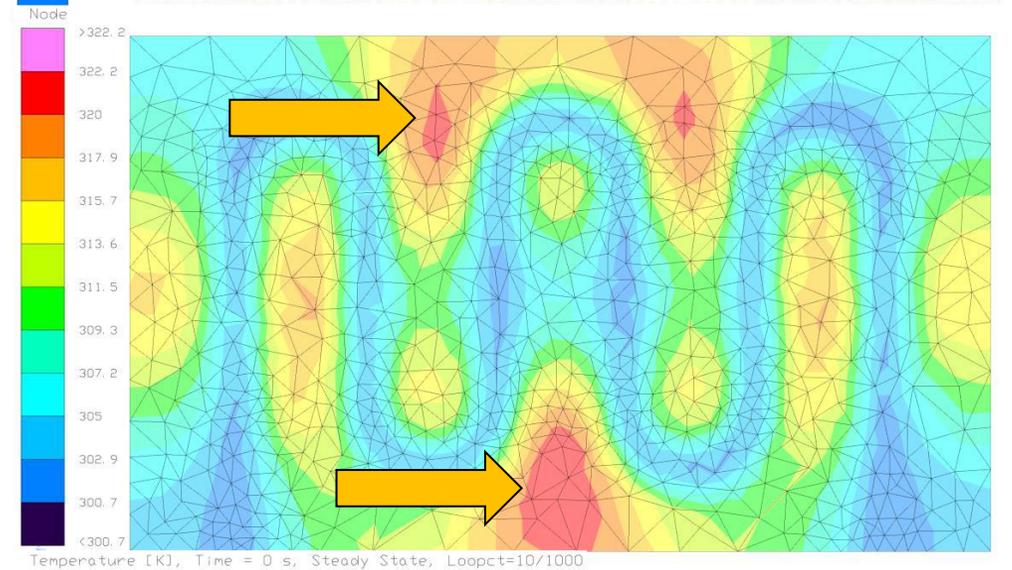
Similar time



Similar results



Similar time





Conclusions



Quadratic Control Volume Conclusions



- Verification
 - Area and volume tests by similarity to Curved Control Volumes
 - Radiation tests by similarity to Curved Control Volumes
 - Transient conduction test matches expected results well
 - Results are comparable to results with existing methods
- Comparison
 - Non-linear temperature distribution requires fewer quadratic control volume elements
 - Postprocessing is smoother with quadratic control volume elements, especially at low resolutions



Considerations



- Fewer elements provide benefits
 - Faster meshing
 - Faster graphics response
 - Limits size growth of collaborative models
- Solution improvements will be model-dependent
 - Quadratic control volume elements will only improve non-linear temperature distributions
 - Quadratic control volume elements will benefit most when the mesh can be coarser than with linear elements
- Solution checking
 - Start with linear elements or curved control volume, if the geometry has curvature
 - Switch to quadratic control volume to evaluate results, speed, and postprocessing without changing the mesh size
- Let the Thermal Desktop team know if you have any issues



References



References

- Bell, D. P., & Panczak, T. (2016). *Verification of Curved Elements for Thermal Analysis*. TFAWS2016-I-07.
- Davies, G. A., Fenner, R. T., & Lewis, R. W. (Eds.). (1993). *Background to Benchmarks*. Glasgow: NAFEMS.
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