Coupled Analysis of FSI

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Engineer Association CCFD

Important Key Words

- Fluid Structure Interface = **FSI**
- Computational Fluid Dynamics = **CFD**
- Pressure Displacement Analysis = **PDA**
- Thermal Stress Analysis = **TSA**

A Part of the Reference

SAE Publications
by Qinyin Fan

PAPERS

Paper Number / Title For more information, click on the Paper Number	Book Number
2008-01-0243 Numerical Analysis of Initial Shape of Nozzle Inject Flow	SP-2172
2007-01-0885 Nonlinear Coupling of Transient Analysis of Thermal Flow and Thermal Stress for T Pipe	V116-6
2006-01-3646 CFD Analysis in Research and Development of Racing Car	P-399
2006-01-1443 CFD Simulation of Pressure Drop in Line Pipe	
2006-01-0589 Coupling of Transient Analysis of Thermal Flow and Thermal Stress for T Pipe	V115-6
2005-01-0516 A Research on Coupled of Transient Analysis of Thermal Flow and Thermal Stress	
2004-01-1345 Coupled Analysis of Thermal Flow and Thermal Stress of An Engine Exhaust Manifold	

Why It Is Important ?

- Automobile (export, engine)
- Construction (bridge, road etc.)
- Electronic parts (base, MEMS)

……anywhere you can meet the needs of the coupled analysis of thermal flow and thermal stress.

What Kind of Analysis Should be ?

- We can divide them into 2 types
  - Pressure on the solid surface

    Fluid and pressure displacement of the solid
  - Convection coefficient on the solid surface

    Fluid and thermal stress of the solid

Pressure on The Solid Surface

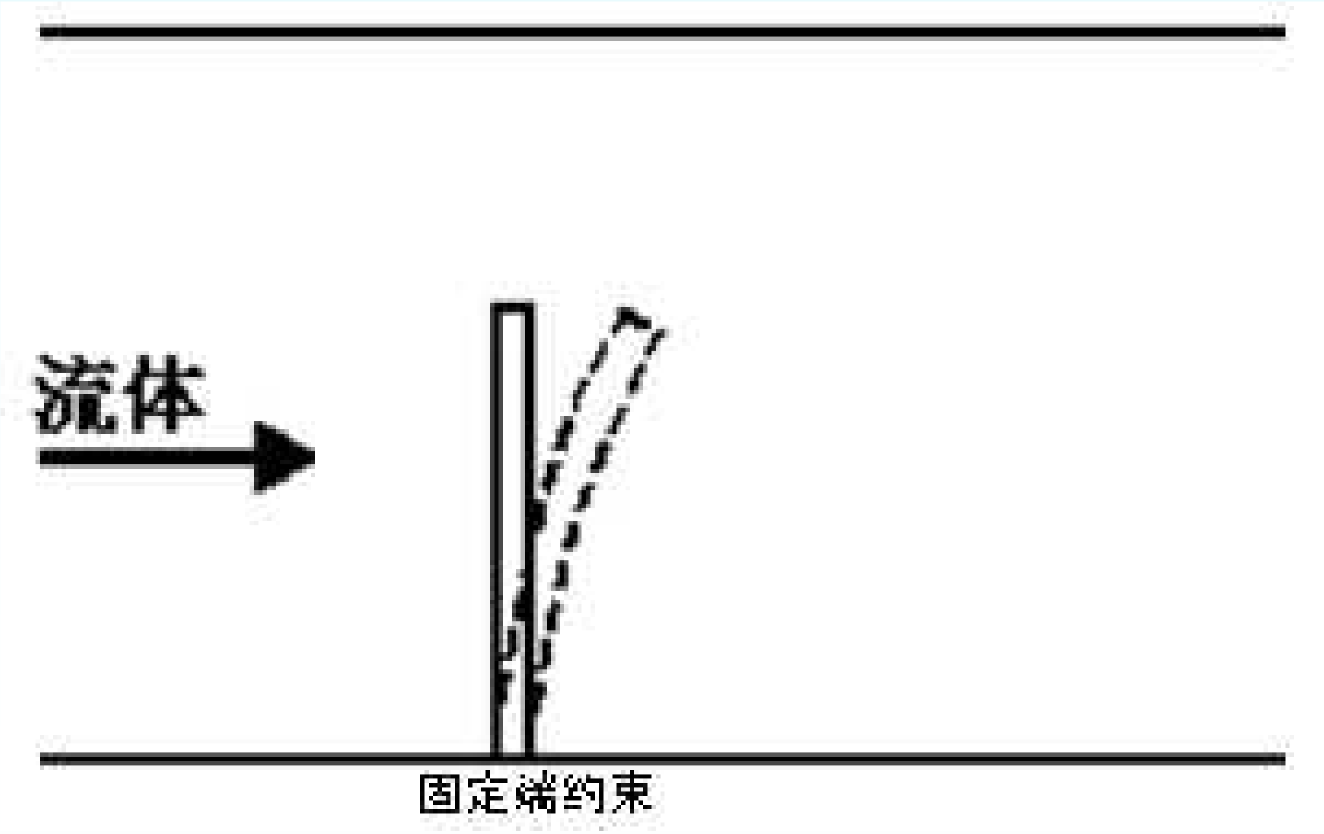
- Steady Static
  - **Small displacement (Linear)**
  - Big displacement

    Linear ,Nonlinear
- Transient
  - **Small displacement (Linear)**
  - Big displacement

    Linear ,Nonlinear
- Fatigue of displacement

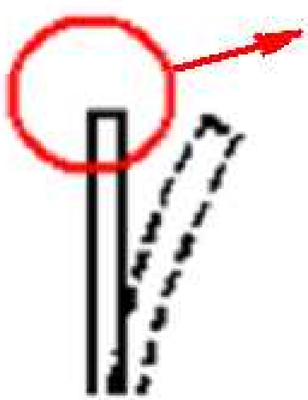
Pressure on The Solid Surface

Steady Static FSI



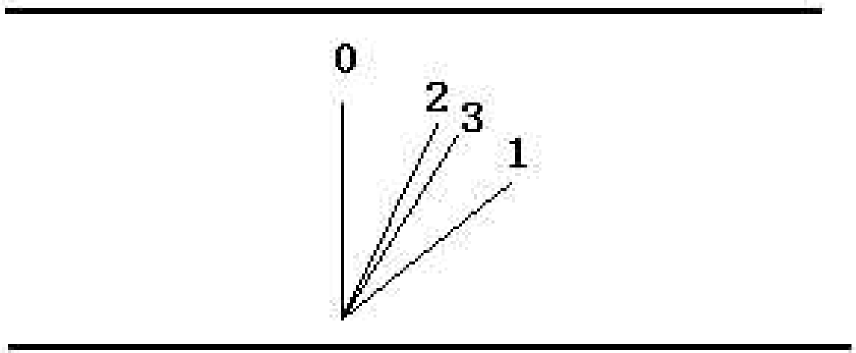
Pressure on The Solid Surface

Steady Static FSI



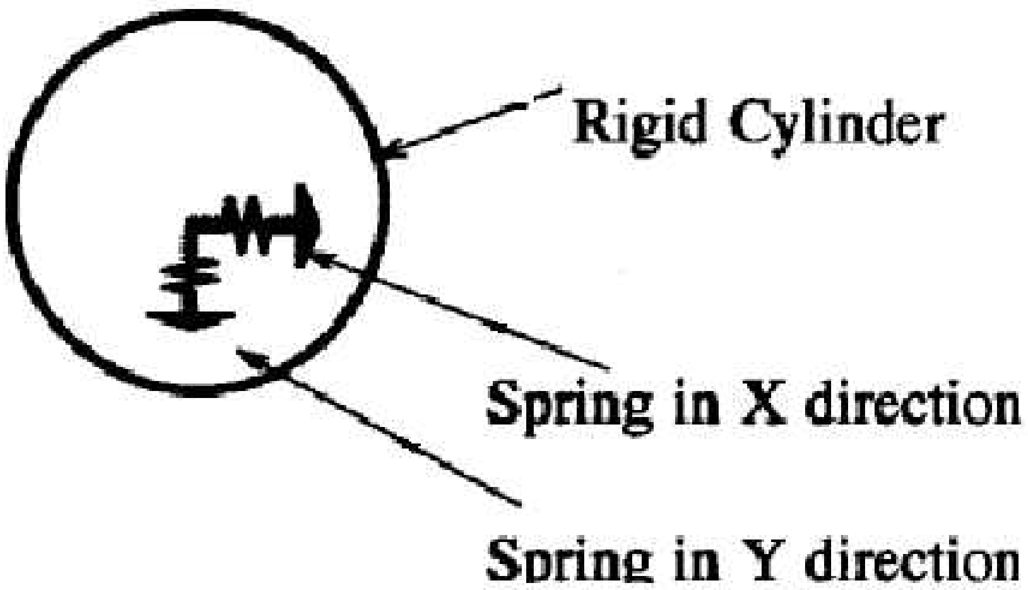
No.	节点号
1	540
2	534
3	556
4	549
5	482

5 monitor points



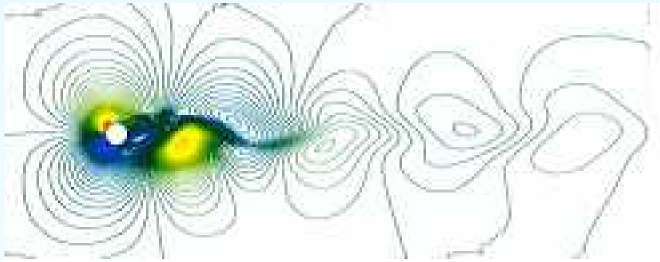
Pressure on The Solid Surface

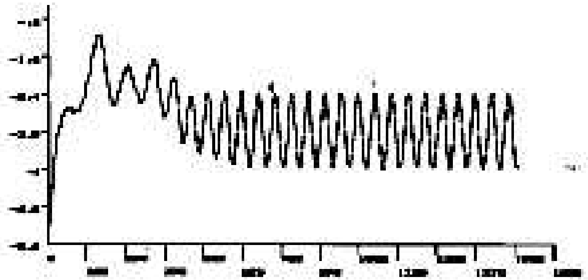
Transient FSI

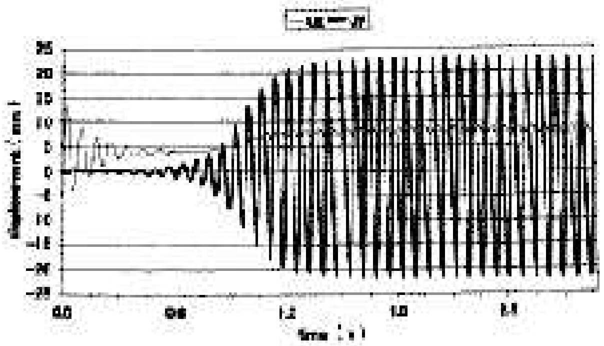


Pressure on The Solid Surface

Transient FSI

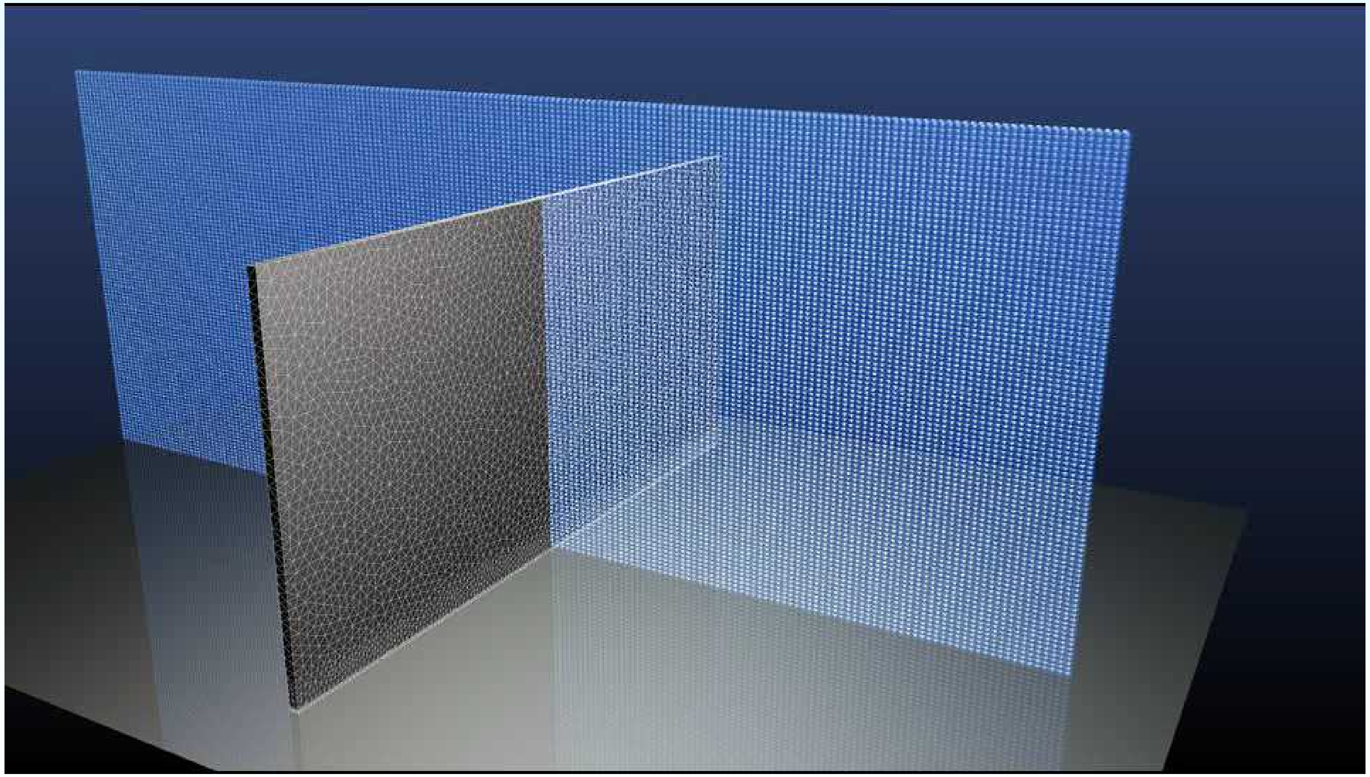






Pressure on The Solid Surface

Transient FSI



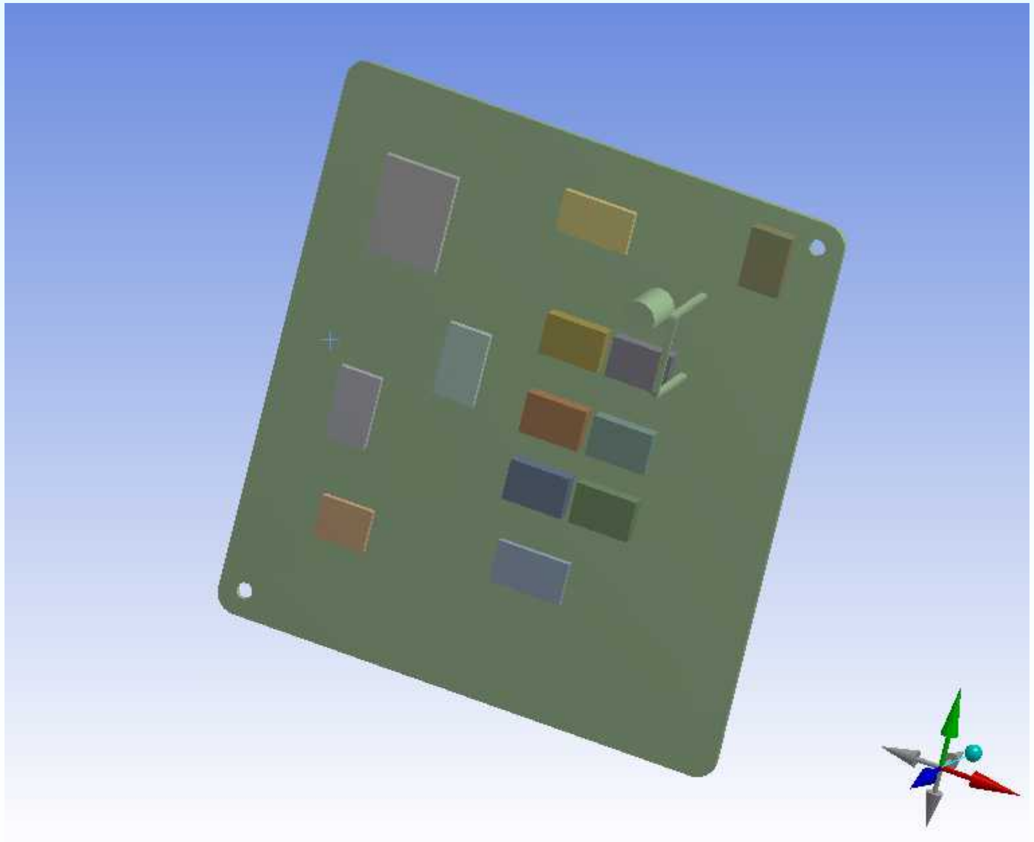
Convection on The Solid Surface

Temperature distribution in the solid part and the thermal stress must be considered

- **Steady Static**
- **Transient**
  - **Linear of Property**
  - Nonlinear of Property
- Fatigue of Thermal Stress

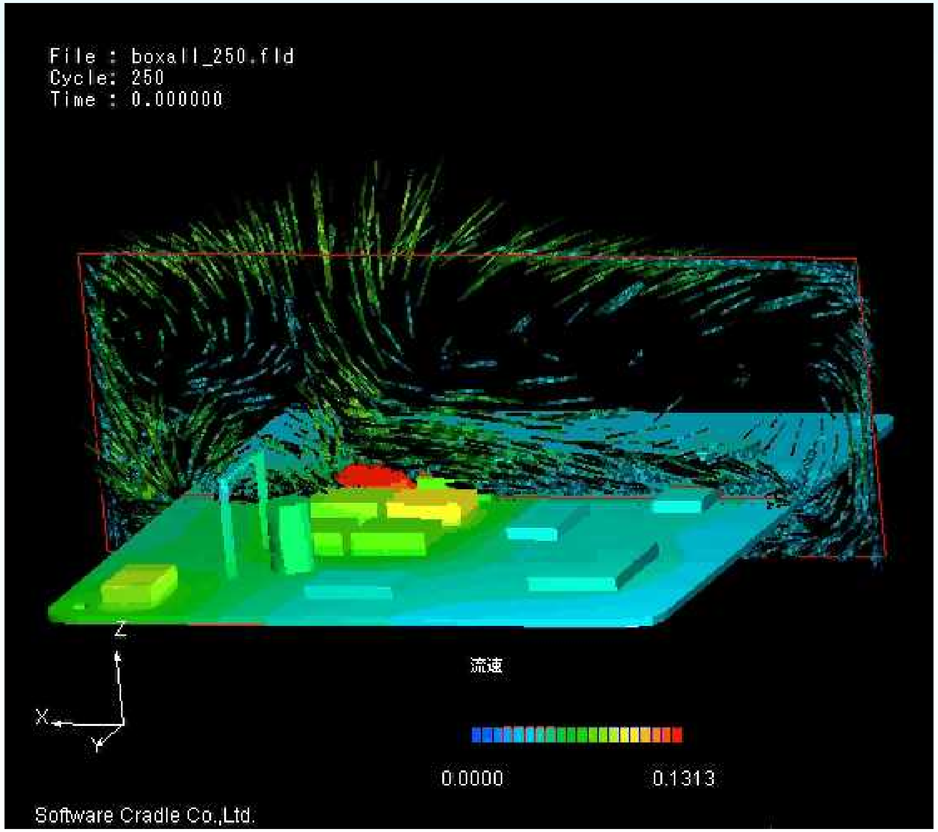
The Status

- Always define a uniform film coefficient at the solid part surface



The Problems

- Effect of the flow can not be estimated correctly, especially for turbulent flow



The Problems

This kind of analysis is not easy to do

- You must understand **CFD** (computational fluid dynamics)
- You must be familiar with thermal stress analysis (**TSA**) too

The Problems

When problem spans both **TSA** and **CFD**, the analysis procedure may be less established. This typically occurs because:

- a stress analysis system and a CFD system tend to be developed independently from each other
- much less attention is paid to the interface between them, although both of CFD and TSA are classic subjects.

How to Solve the Problems (1)

Experiment:

- To measure the film coefficient can define a reasonable film coefficient, but it takes cost and time, and the measure points are limited

Too difficult or impossible

How to Solve the Problems(2)

Calculation(1):

A few iterations between stages might be necessary to obtain a converged solution.

- Inner and outer thermal flow around (not including) the solid part are simulated to get the correct film coefficient for thermal and thermal stress analysis of solid part

3 steps : thermal flow analysis (flow part)
thermal analysis (solid part)
thermal stress analysis (solid part)

How to Solve the Problems(3)

Calculation(2):

- Inner and outer thermal flow around (including) the solid part are simulated to get the correct solid temperature for thermal stress analysis directly

2 steps : thermal flow analysis (solid +flow)
thermal stress analysis (solid)

The Possible Choices of CFD+TSA

FVM CFD calculation > FEM structure analysis

- FVM > FEM

FEM CFD calculation > FEM structure analysis

- FEM > FEM

  - FVM (finite volume method)
  - FEM (finite element method)

    - Much easier than experiments

Investigation And Comparison

FVM > FEM: SC/Tetra + ANSYS

FEM > FEM: FLOTRAN + ANSYS

Are used for our investigation and comparison

- In our investigation, we have used one CFD system, SC/Tetra developed by authors [1]. To solve for the thermal stress field, we have used a commercial structure system ANSYS developed by ANSYS.Inc. Both two applications are capable of solving for temperature fields.

Investigation And Comparison

FVM > FEM: SC/Tetra + ANSYS

FEM > FEM: FLOTRAN + ANSYS

Are used for our investigation
and comparison

- These solvers are chosen because they are readily available to the authors. But authors insist that the concepts introduced here can be used for coupling between any CFD and any structure applications developed by oneself or of commercial software.

SC/Tetra

supports hexahedral, prismatic, pyramidal and tetrahedral elements, i.e. a hybrid mesh,

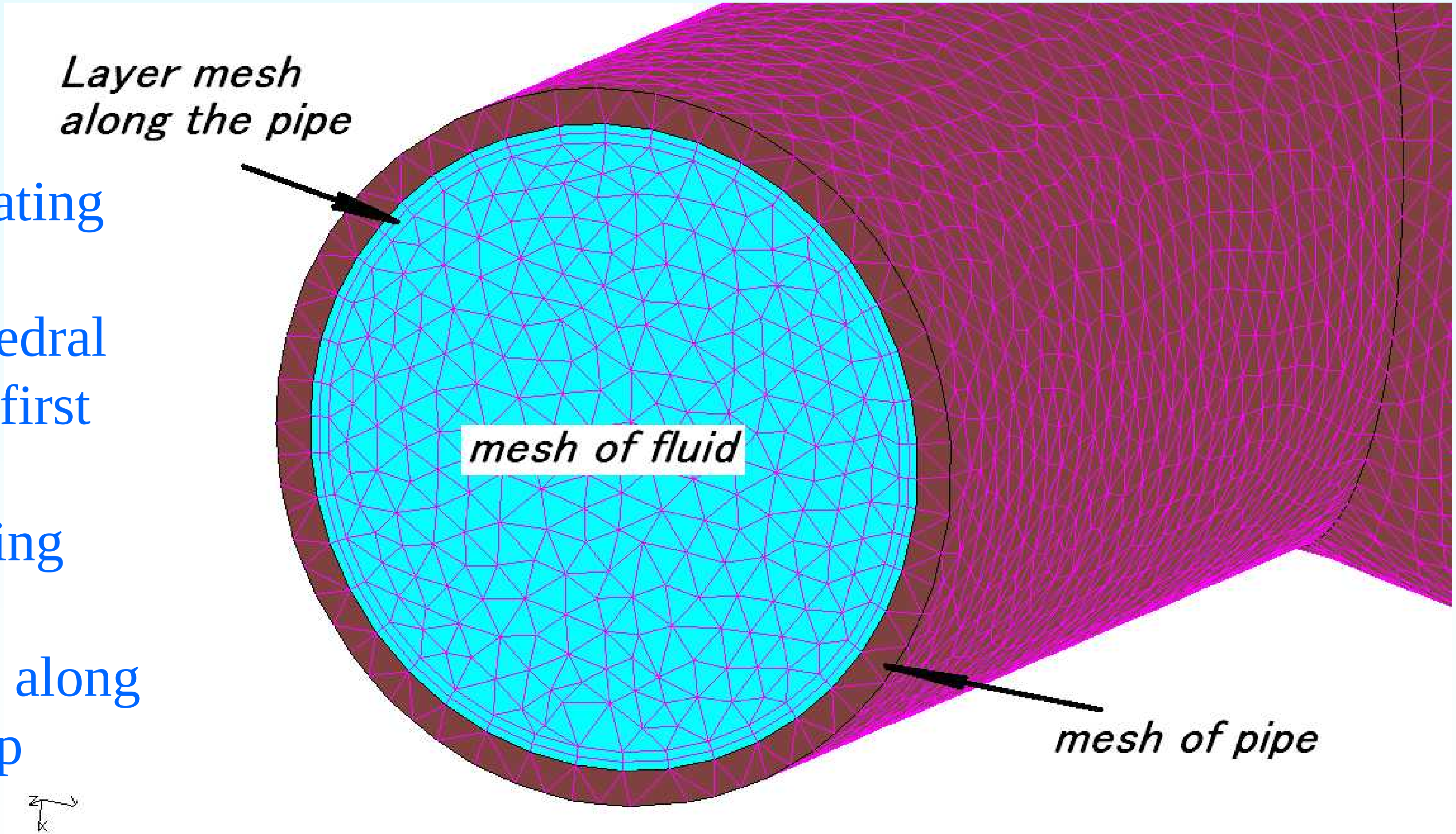
generating a tetrahedral mesh first and inserting prism layers along no-slip walls.

all variables are defined on nodes of elements.

can be used easily to make a complex mesh model and has a good interface with FEM structure analysis software.

SC/Tetra

generating a tetrahedral mesh first and inserting prism layers along no-slip walls.



FLOTRAN + ANSYS

- Various element types
- for convenient +speed, 72
- for convenient + accuracy, 92
- for accuracy, 95
- 45 must be paid attention

There is not any limit for the mesh shape, But FLOTRAN can not be easily used for a complex model

ICEM and AI-Environment

supports hybrid mesh too

generating a tetrahedral mesh first and inserting prism layers along no-slip walls just in the fluid side

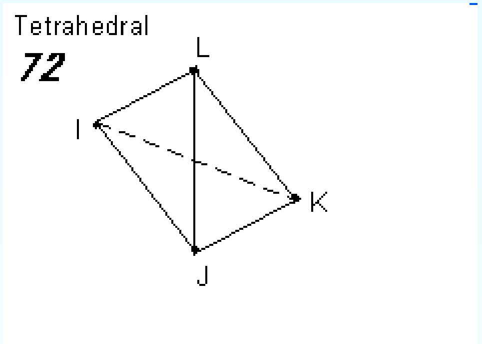
ICEM or AI-Environment will help us too

Element Type

The marching of element shapes is not easy

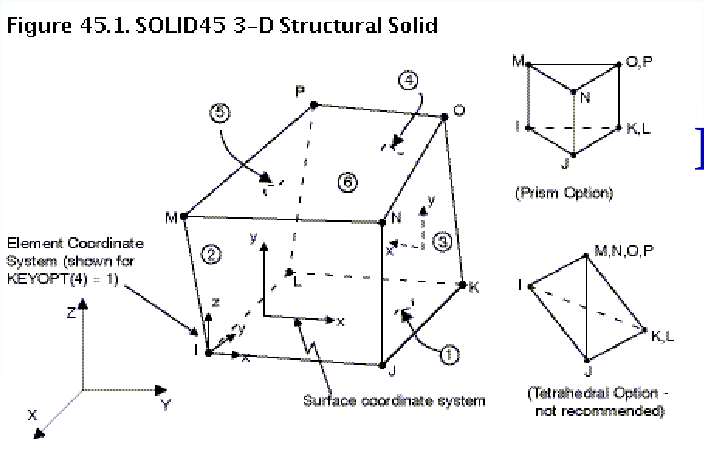
Element Type (first order)

first order tetrahedral 4 node element,



ET 72 in ANSYS

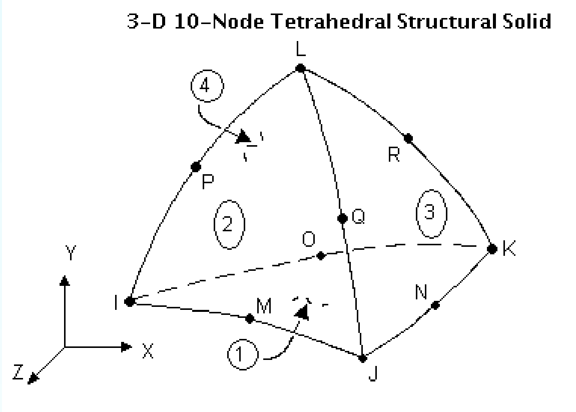
degenerate first order tetrahedral 8 node element



ET 45 in ANSYS

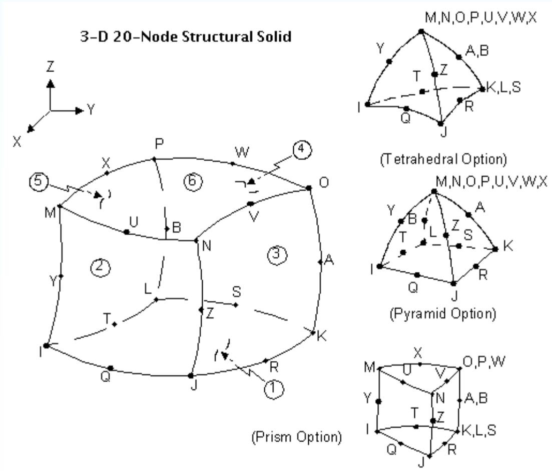
Element Type (second order)

quadratic displacement tetrahedral 10 node element



ET 92 in ANSYS

degenerate quadratic displacement tetrahedral 20 node element



ET 95 in ANSYS

Element Type

- Different element types

    72

    45

    92

    95

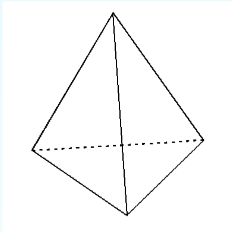
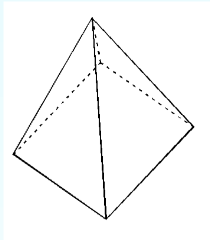
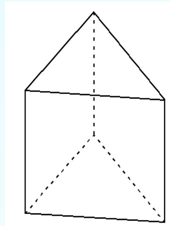
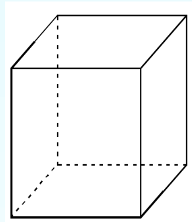
  are used in the thermal stress analysis for comparison of element type effect.

Element Type

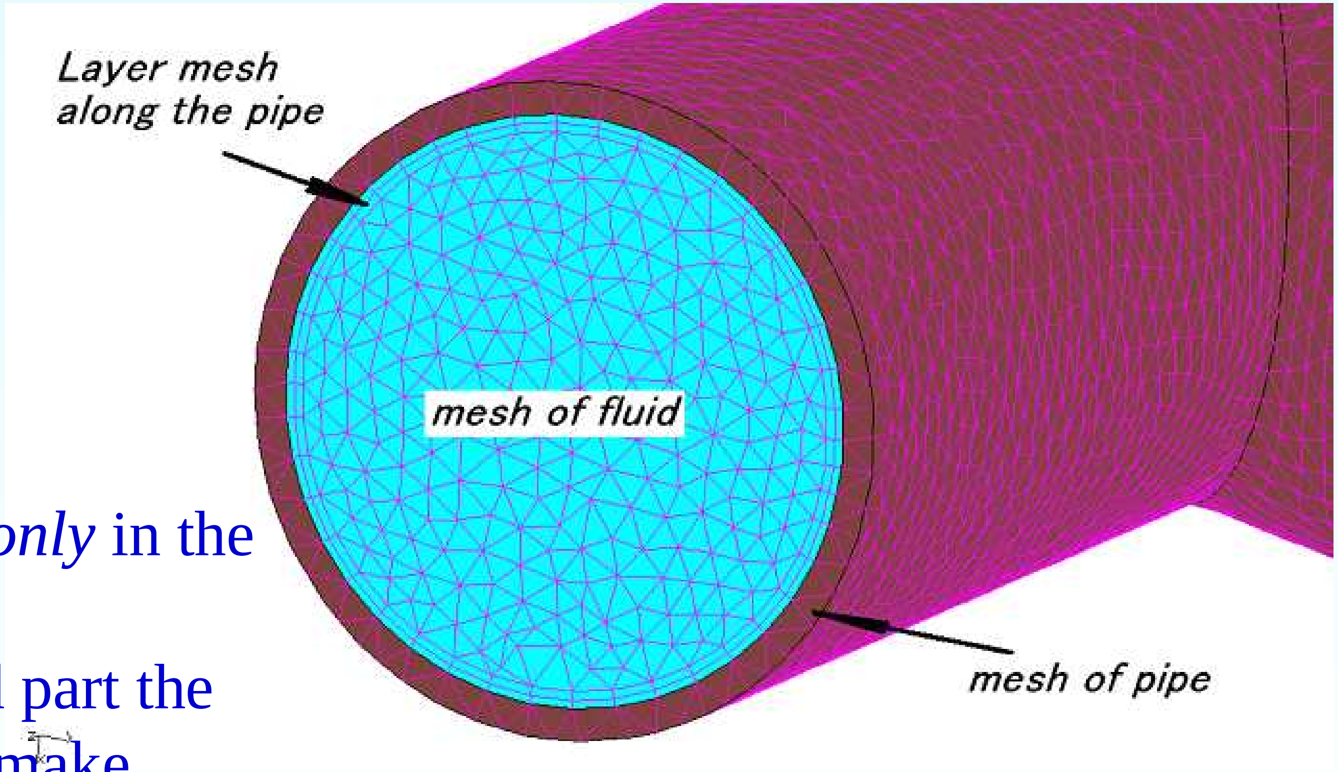
- CFD analysis can contain hybrid elements in the solid part.
- In TSA second order degenerate hybrid (such as element type 95) must be considered too.
- This is a typical difficult of coupling between a CFD system and a structure system for Direct Conversion.

Other Software

The possible output element shape

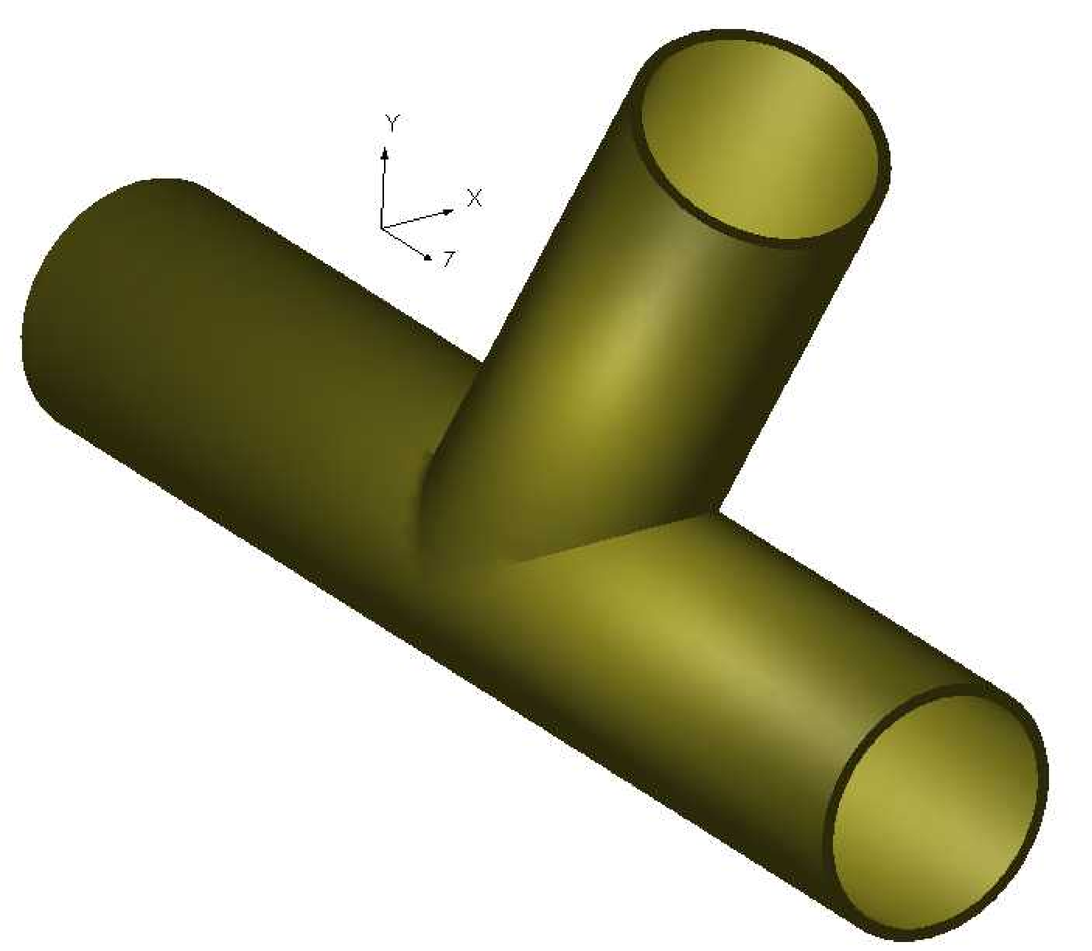
				
ANSYS	○	○	○	○
DesignSpace	○	○	○	○
NASTRAN	○	○	○	○
I-DEAS	○		○	○
ABAQUS	○			○

SC/Tetra



Hybrid elements *only* in the fluid part
Only tetra in solid part the coupling process make Direct Conversion very simple and easy.

Typical Model



Calculation conditions

- The inner diameter of the main pipe is 2.0m.
- The inner diameter of the branch pipe is 1.4m.
- The thickness of the pipe is 0.1m.
- The inlet velocity is 0.7 m/s.
- The inlet temperature is773 K.
- The velocity of inlet 2 is 0.4 m/s.
- The temperature of inlet 2 is 573 K.
- The pressure is 0 Pa at the outlet.

Calculation conditions(2)

- The working fluid is incompressible air
- density is 1.2050 kg/m^3
- viscosity is 1.8135e-05 kg/m·s
- thermal conductivity is 0.02574 W/m·K
- specific heat is 1004.0 J/Kg·K

Calculation conditions(3)

- The material of the pipe is iron.
- density is 7871.40 kg/m^3.
- Young's modulus is 210e9 N/m.
- Poisson's ratio is 0.3.
- thermal conductivity is 81.168 W/m·K.
- specific heat is 439.2 J/Kg·K.
- coefficient of linear thermal expansion is 16.6e-6 K^{-1}.

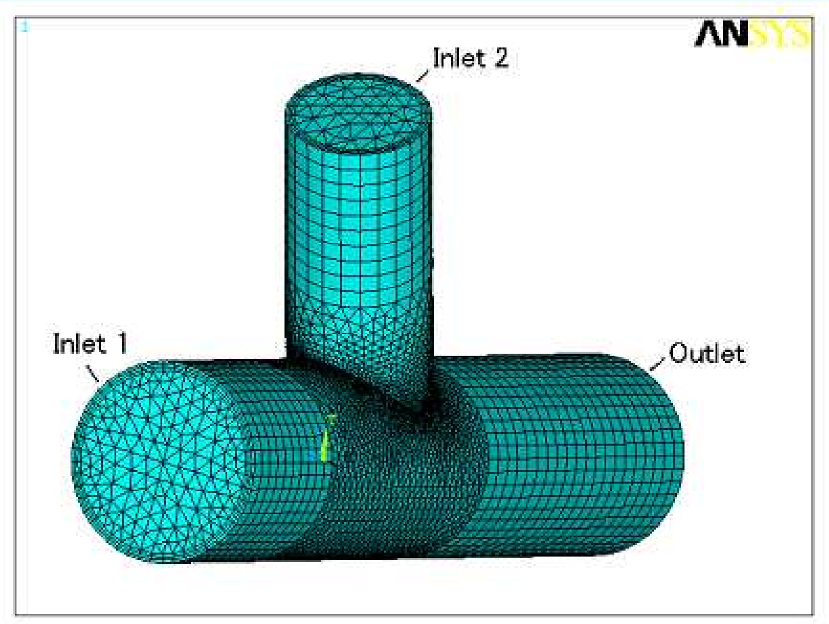
4 approaches

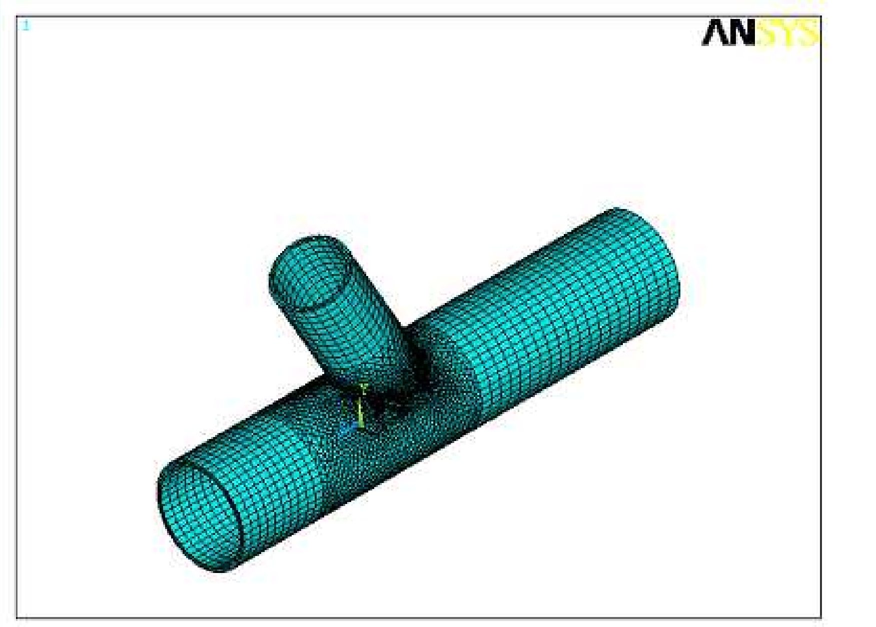
CFD Delivered Data → **TSA**

- 0) FLOTRAN(ET142) – ANSYS(ET95)
  T to the same nodes
- 1) SC/Tetra – ANSYS (ET95,72,92)
  T to nodes
- 2) SC/Tetra – ANSYS(ET95,72,92)
  H mapped to surface
- 3) SC/Tetra – ANSYS(ET95,72,92)
  T mapped to nodes

4 approaches(0)

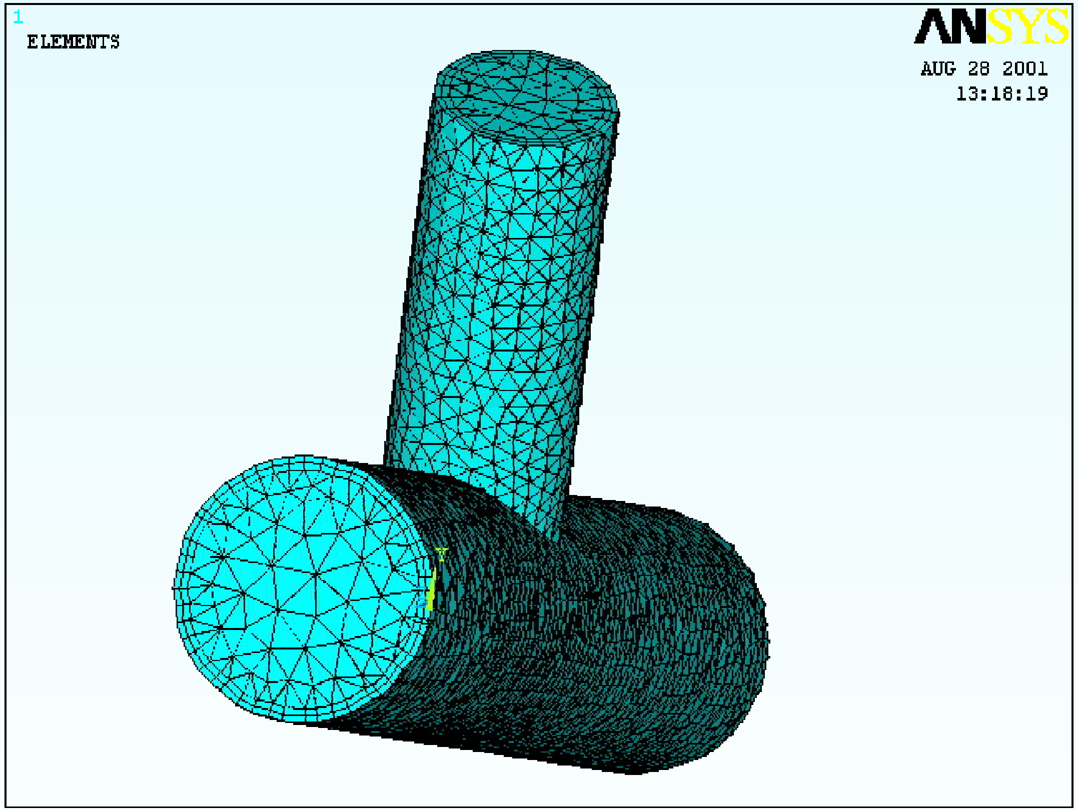
FLOTRAN(ET142) – ANSYS(ET95)
T to the same nodes





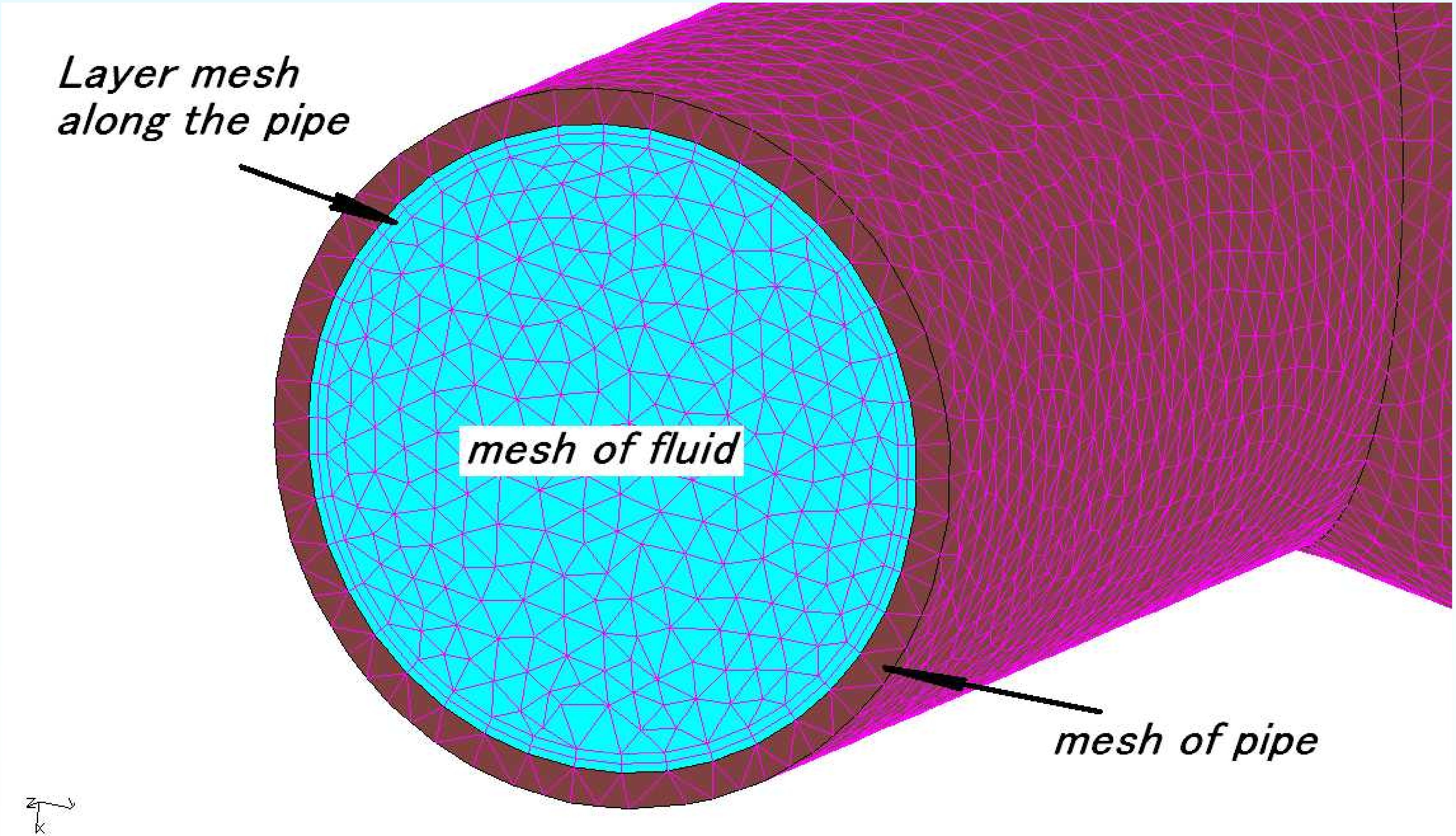
Same nodes and same result temperature

4 approaches(0)



No boundary layer mesh in flow domain in FLOTRAN model.

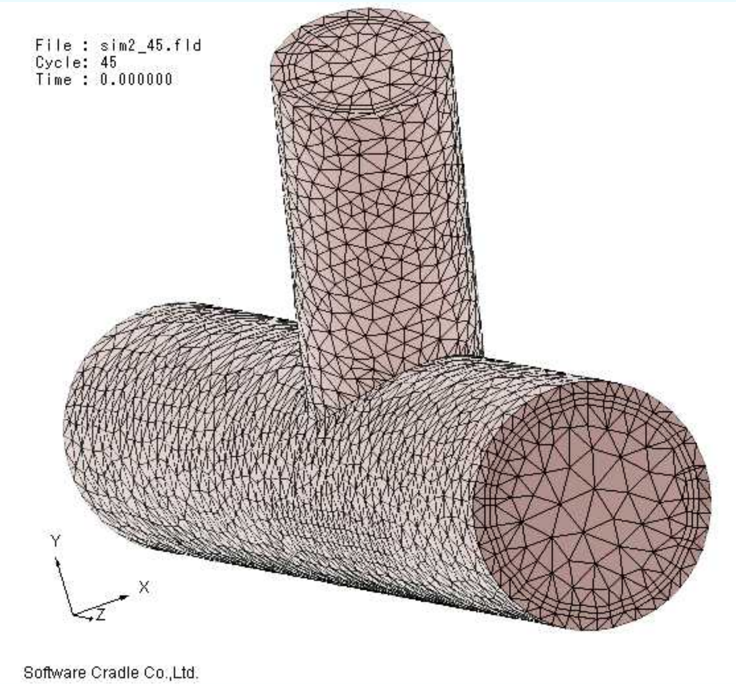
4 approaches(1)

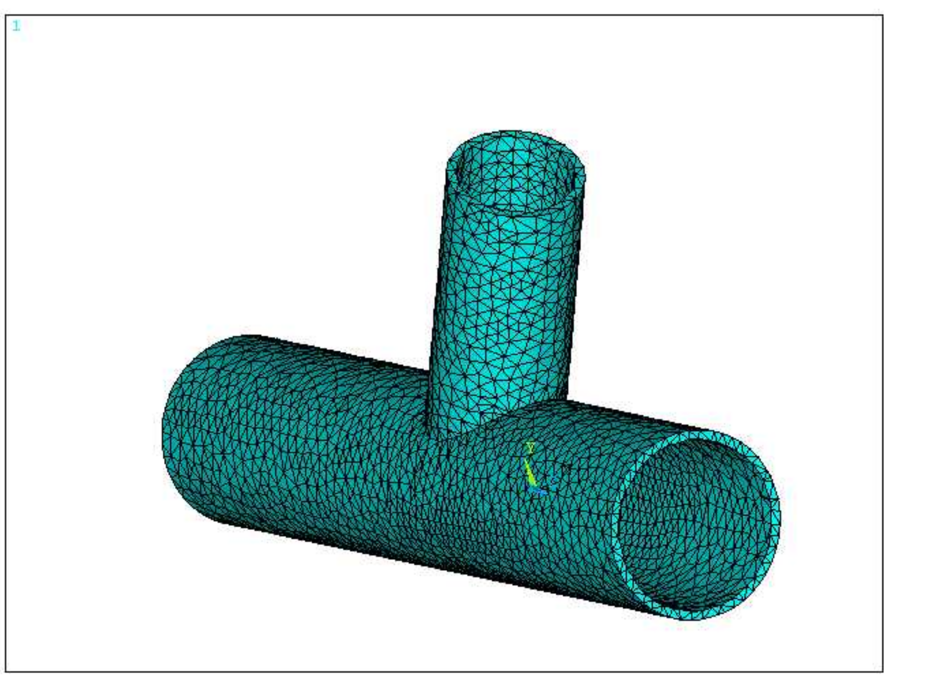


4 approaches(1)

SC/Tetra – ANSYS(ET95,72,92)

T to the same nodes



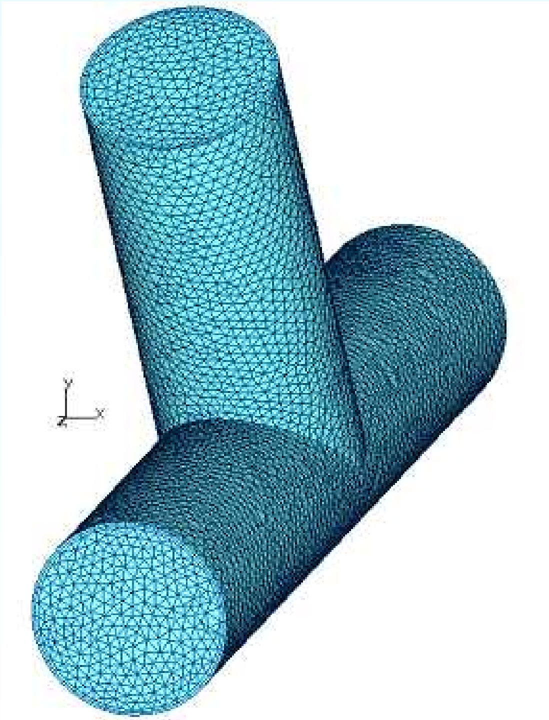


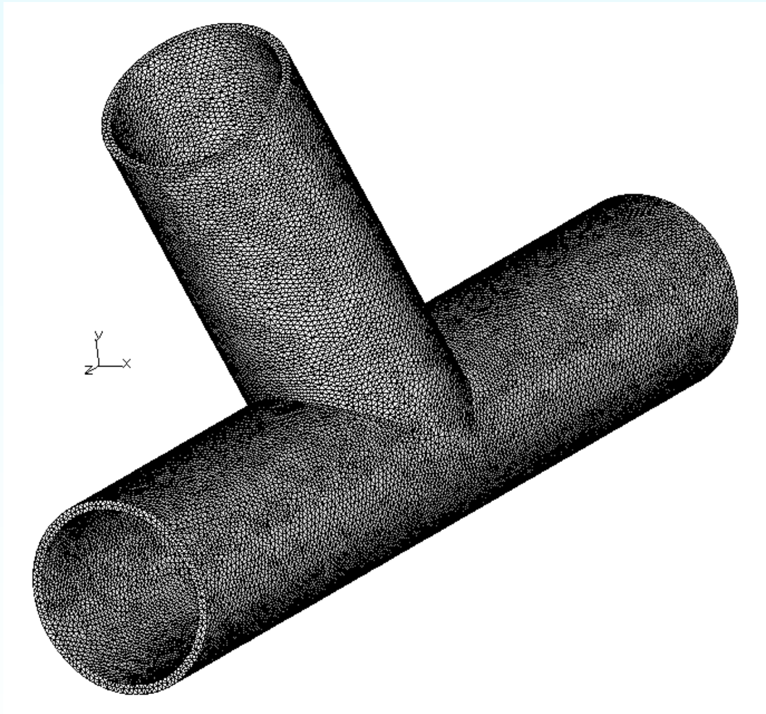
Same nodes and same result temperature on solid mesh nodes which are a part of the whole mesh

4 approaches(2)

SC/Tetra – ANSYS(ET95,72,92)

H is mapped to new surface nodes



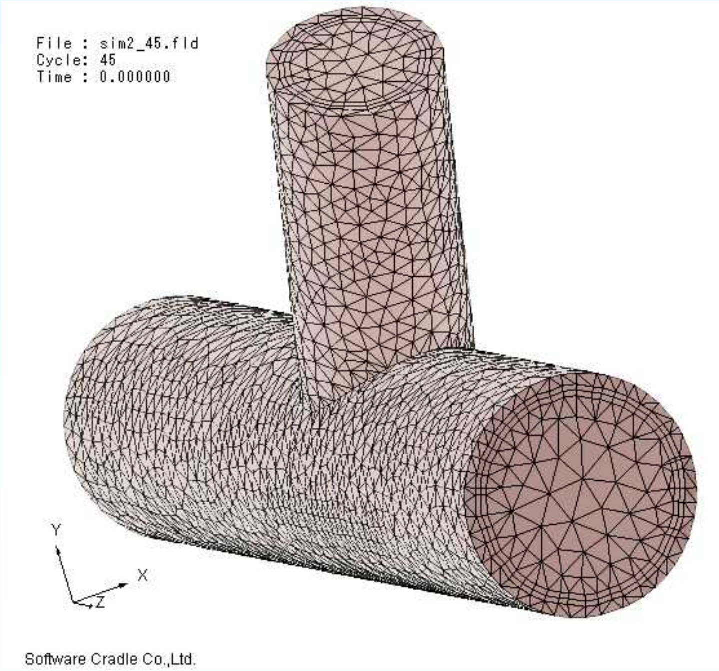


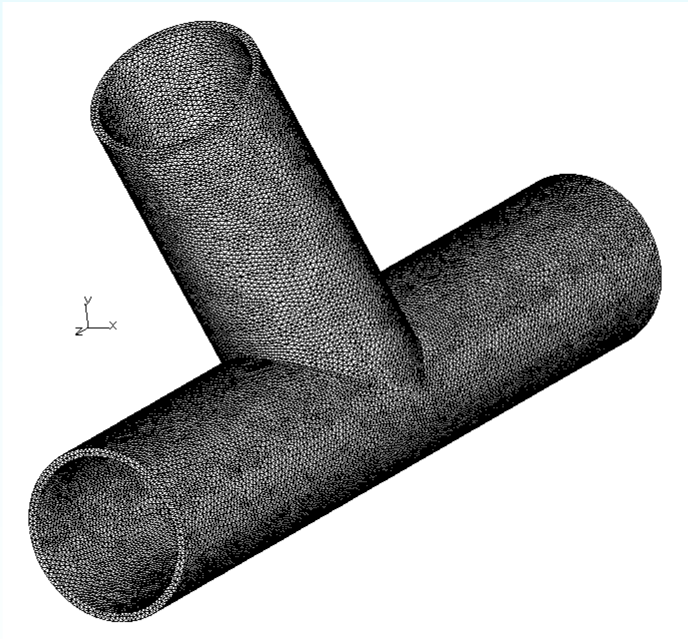
Different nodes and mapped result temperature

4 approaches(3)

SC/Tetra – ANSYS(ET95,72,92)

T mapped to volume new nodes





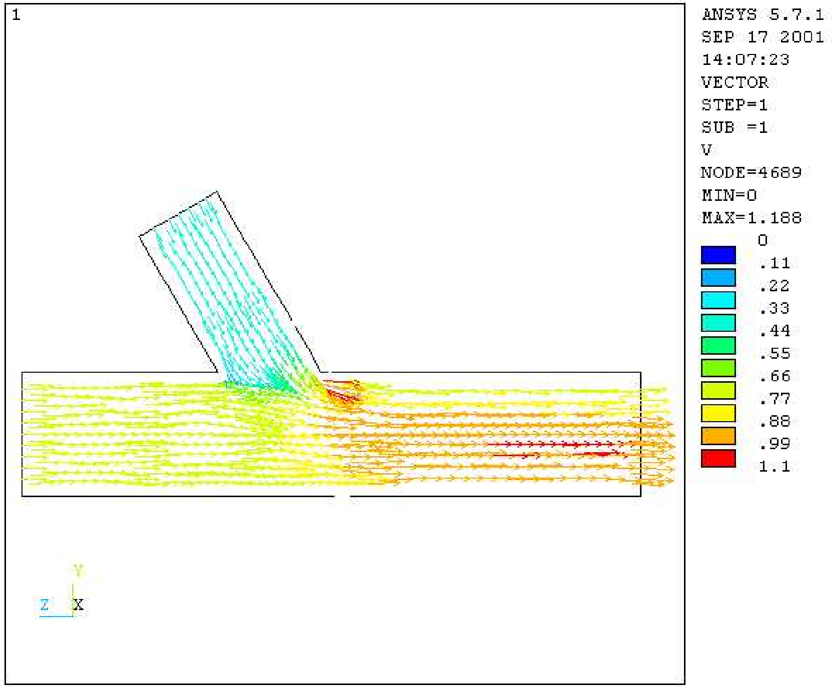
Meshes do not need consistency on the common boundary surface

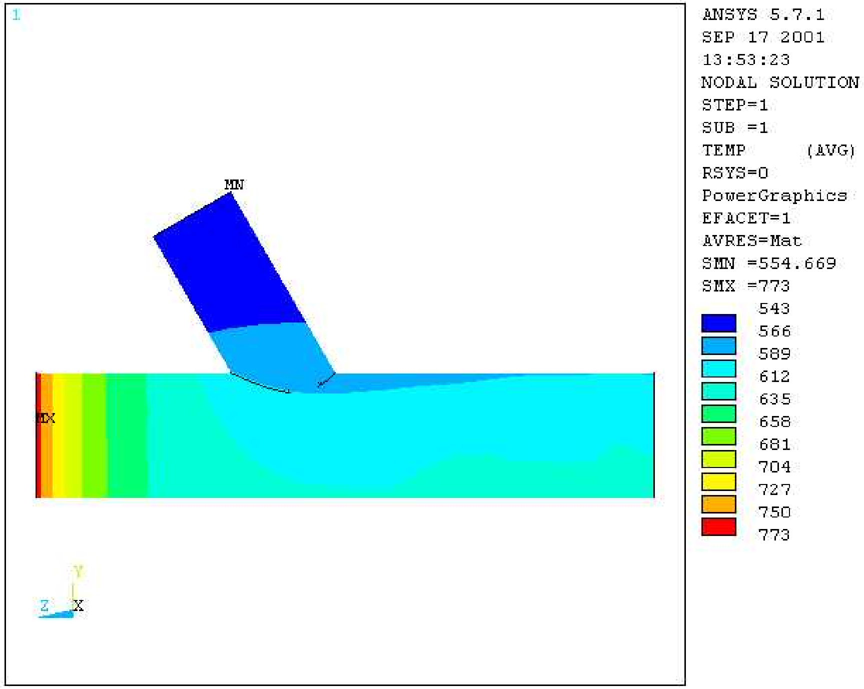
4 approaches

Case	Mesh size		
	CFD	*TSA*	
1	67624	19630	**Direct Conversion**
2	FLOTRAN	16116	**Direct Conversion**
3	51531	59439	**Surface Mapping**
4	SC/Tetra	59439	**Volume Mapping**

Table 2: Number of elements in computational mesh. Both solid and fluid elements are counted in CFD column.

Results of case 0



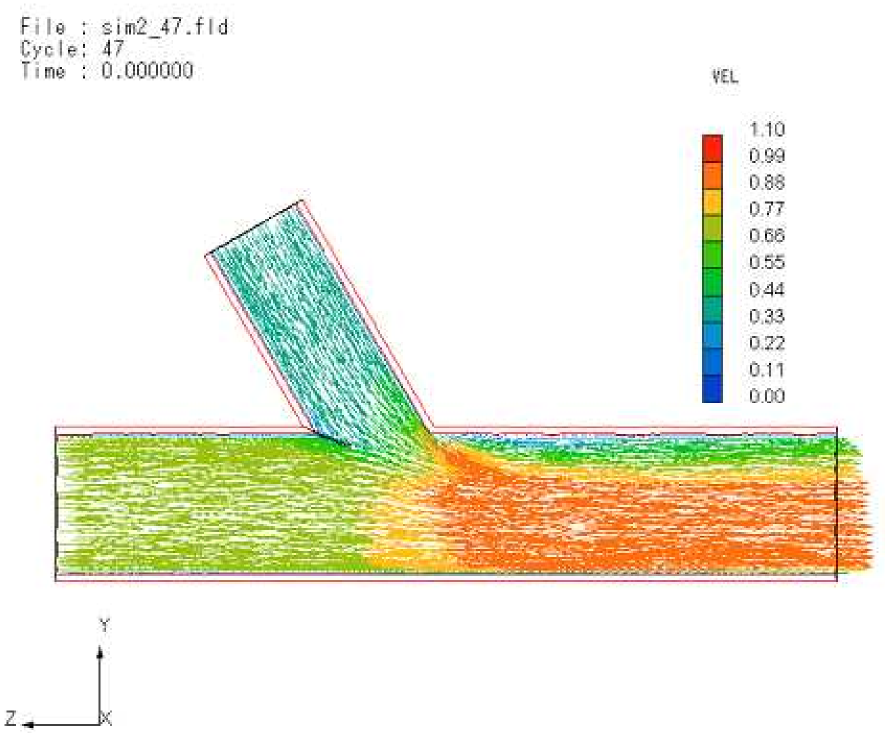


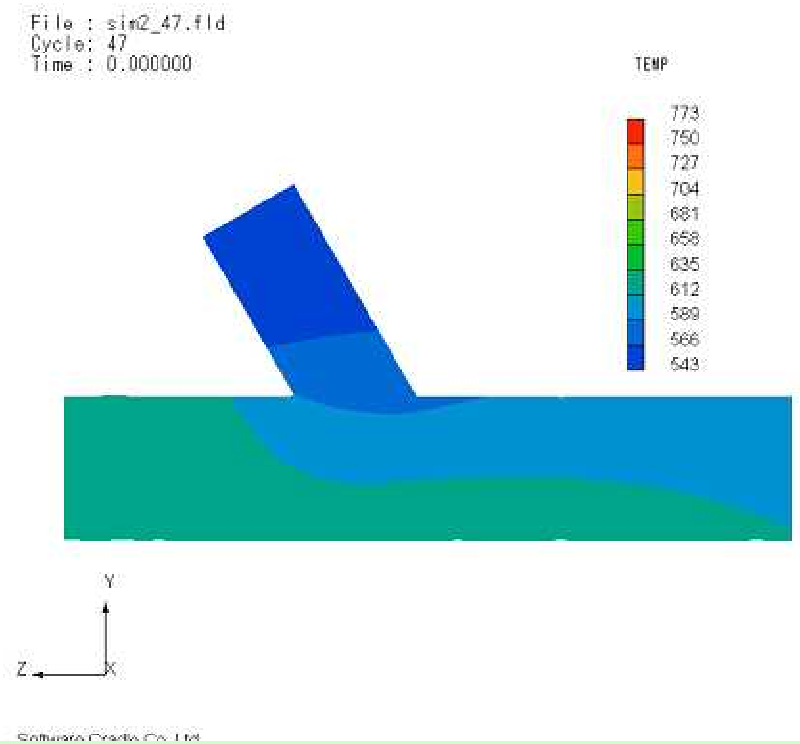
The CFD result of Case 0

Left: velocity field on center cut plane.

Right: temperature distribution on the outer surface of the pipe.

Results of case 1





The CFD result of Case 1.

Left: velocity field on center cut plane.

Right: temperature distribution on the outer surface of the pipe.

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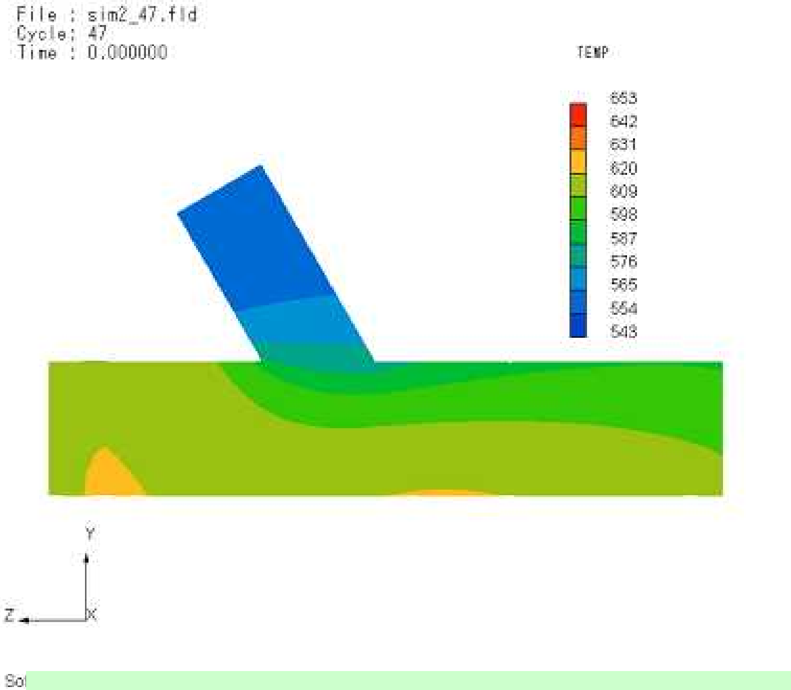
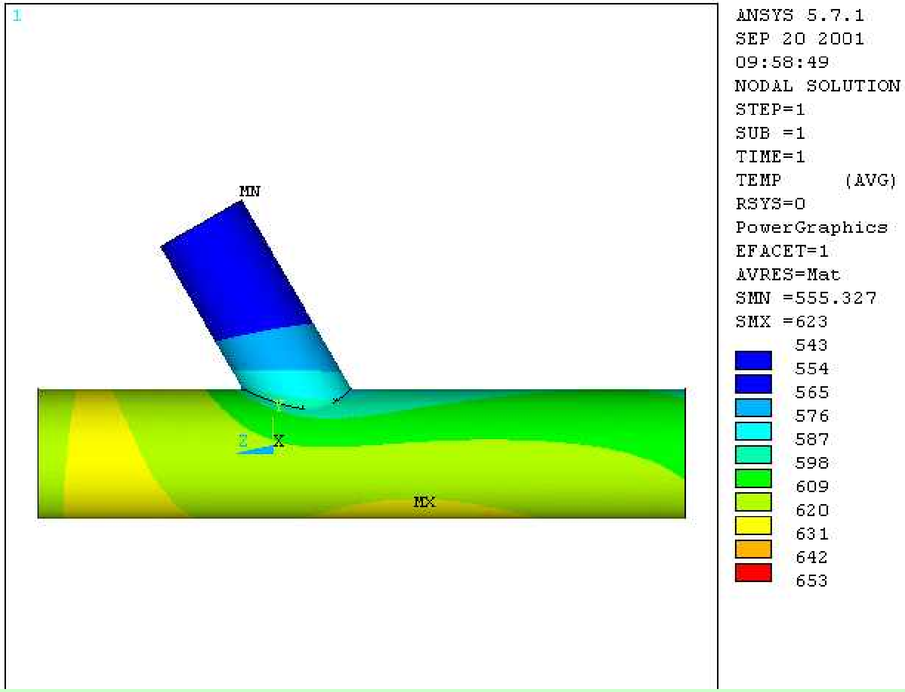
Comparison of case 0 and 1



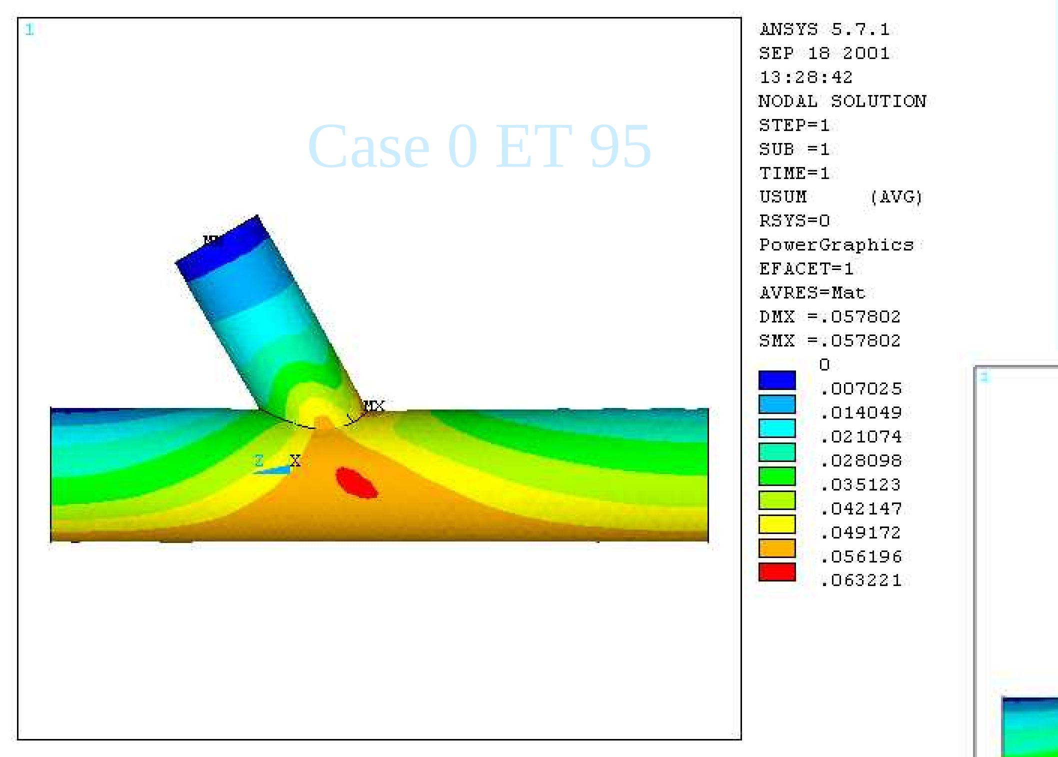


Temperature distribution on the outer surface of the pipe.

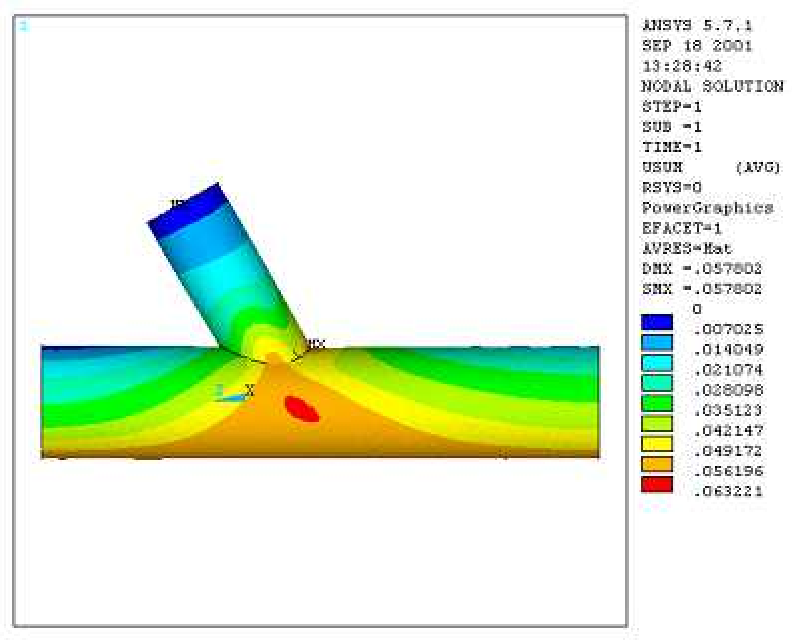
Left: Case 1

Right: Case 0 (obtained using ANSYS).

Thermal Stress Comparison(1)



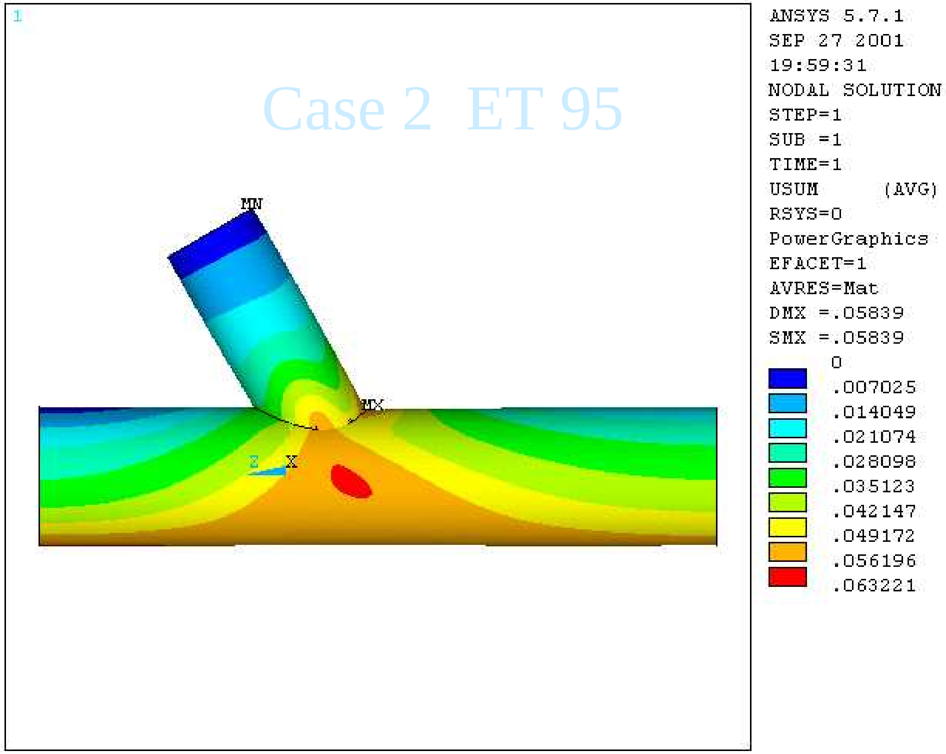
Case 1 ET 95

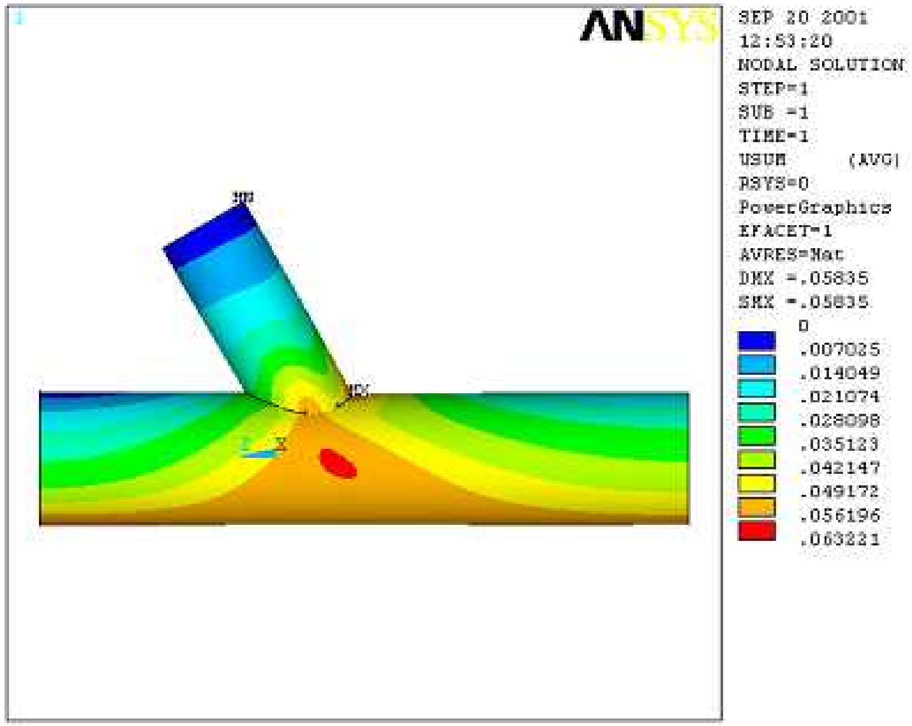


Conclusion of Transfer Method

- The similar results of case 0 and 1 shows that a reasonable accuracy can be obtained using Direct Conversion Method of transferring temperature fields from SC/Tetra to ANSYS as well as FLOTRAN to ANSYS.

Thermal Stress Comparison(2)

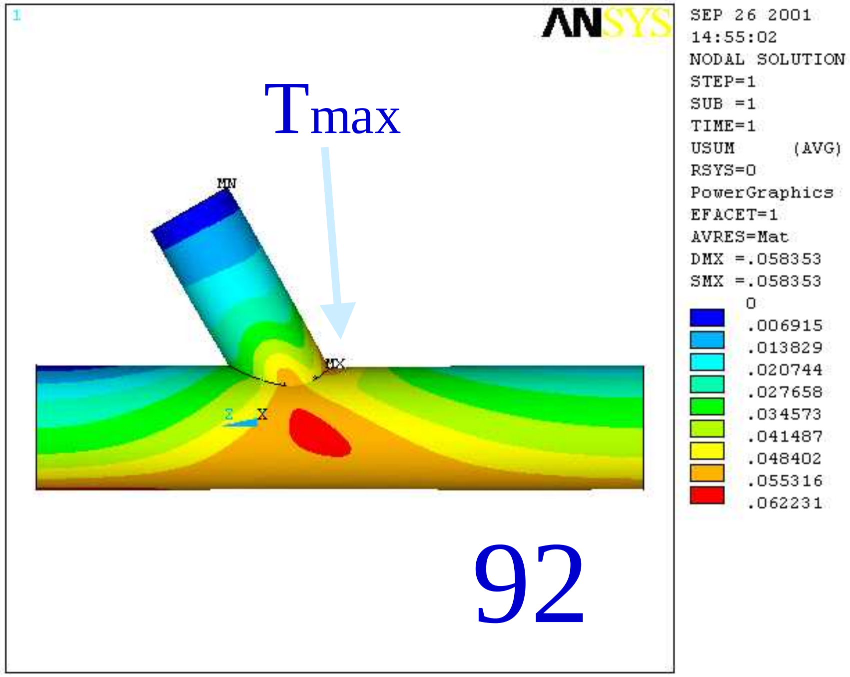


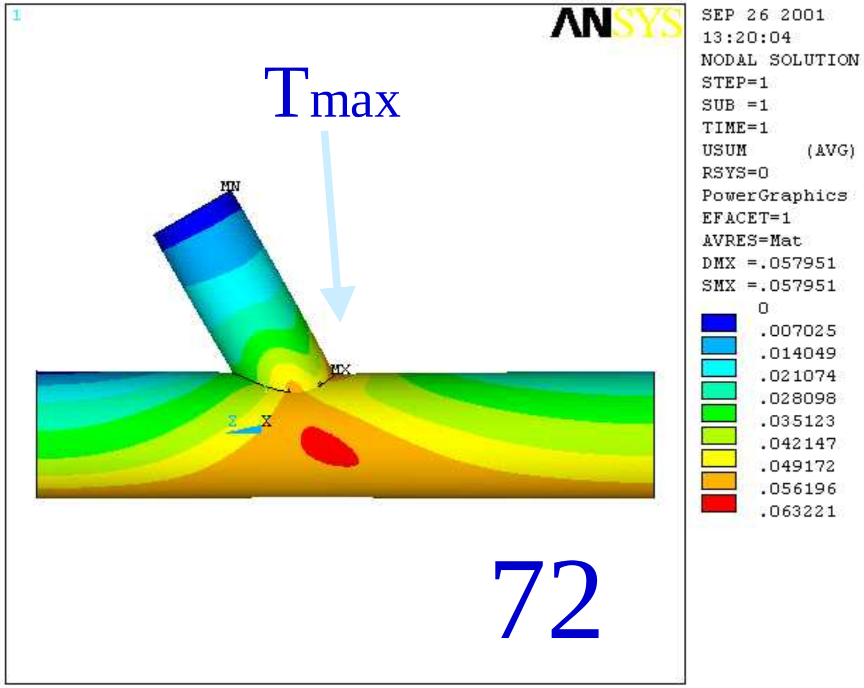


Conclusion of Transfer Method

- The results in Case 2 and Case 3 are nearly identical and shows that the Surface Mapping and the Volume Mapping can work equally well.
- The results in all 4 cases are nearly identical and shows that the Direct conversion, Surface mapping and the Volume mapping can work equally well.

Effect of Element Type (ET)





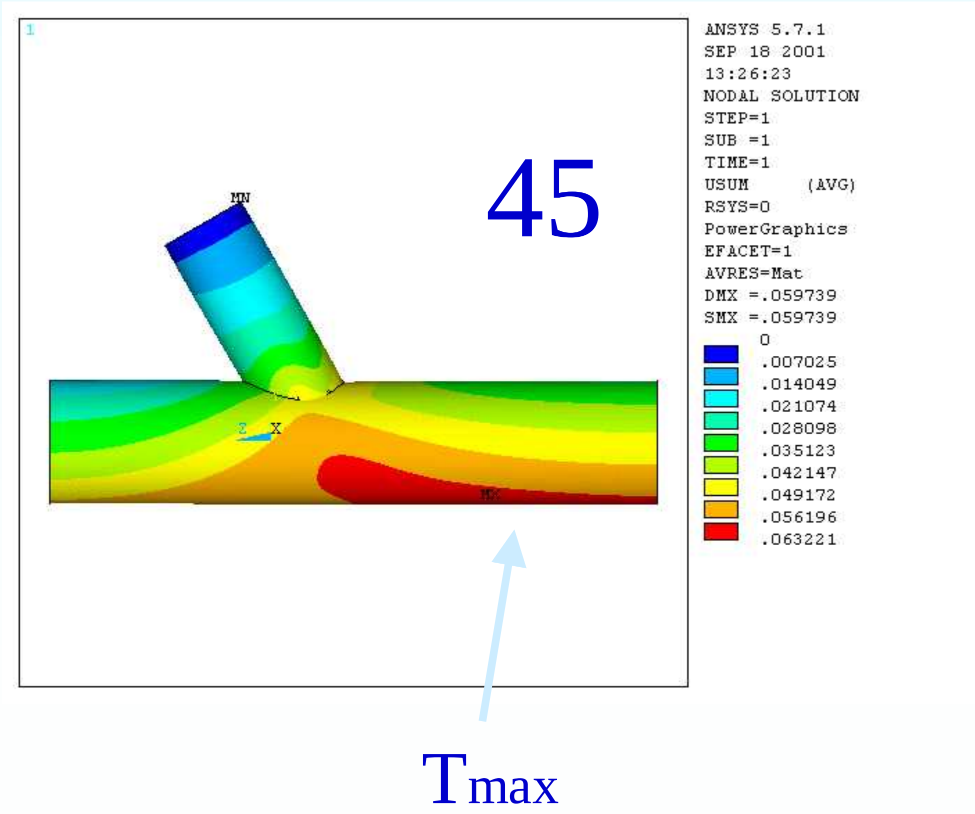
Tmax

Effect of Element Type

look out

45 is typical 3D "constant strain triangle" element [5]

Low order Et 95 will be the same.

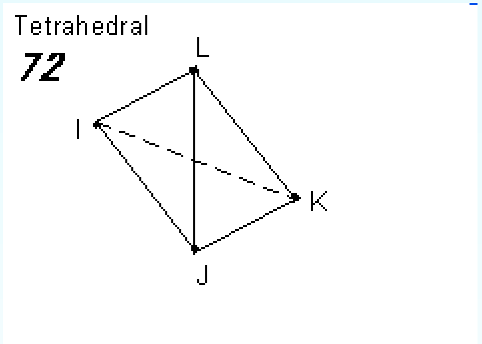


Effect of Element Type

- Different element types
- 72
- 45
- 92
- 95
- are used in the thermal stress analysis for comparison of element type effect.

Effect of Element Type (first order)

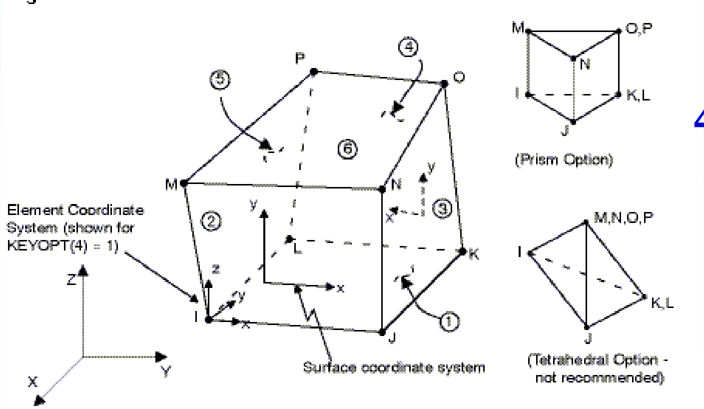
first order tetrahedral 4 node element,



72

degenerate first order tetrahedral 8 node element

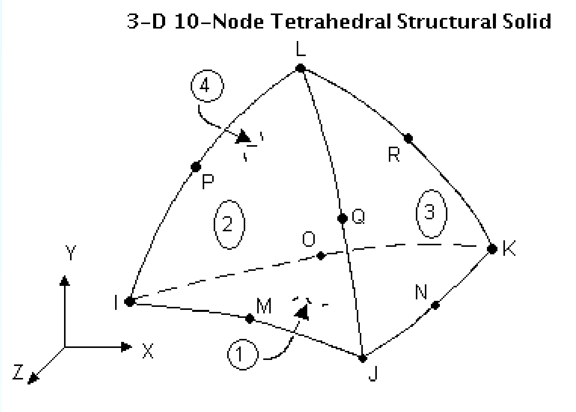
Figure 45.1. SOLID45 3-D Structural Solid



45

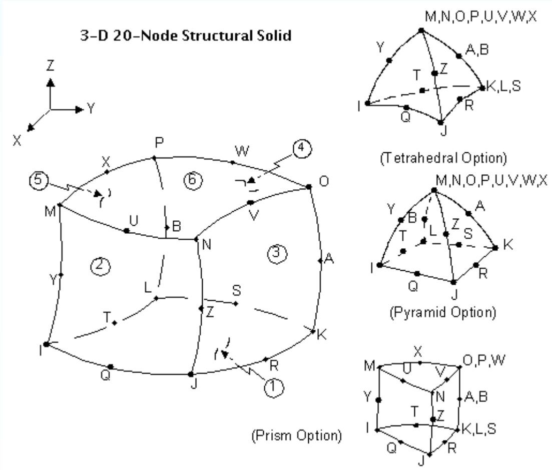
Effect of Element Type (second order)

quadratic displacement tetrahedral 10 node element



92

degenerate quadratic displacement tetrahedral 20 node element



95

Conclusion of Element Type

- Element type 92 gives the closest result to type 95.
- Element type 45 cannot produce a good result in bending even if a finer mesh is used, because it is a typical 3D “constant strain triangle” of degenerate tetrahedron
- Second order elements (type 92 and 95) give better results compared to first order element (type 72).

Conclusion of Element Type

The Order of Priority

95 > 92 > 72

> 45 Hex

> ~~45 Tetra or 95 Low order Tetra~~

Example of Exhaust Port

Using SC/Tetra to do
an analysis including solid part

Direct Conversion

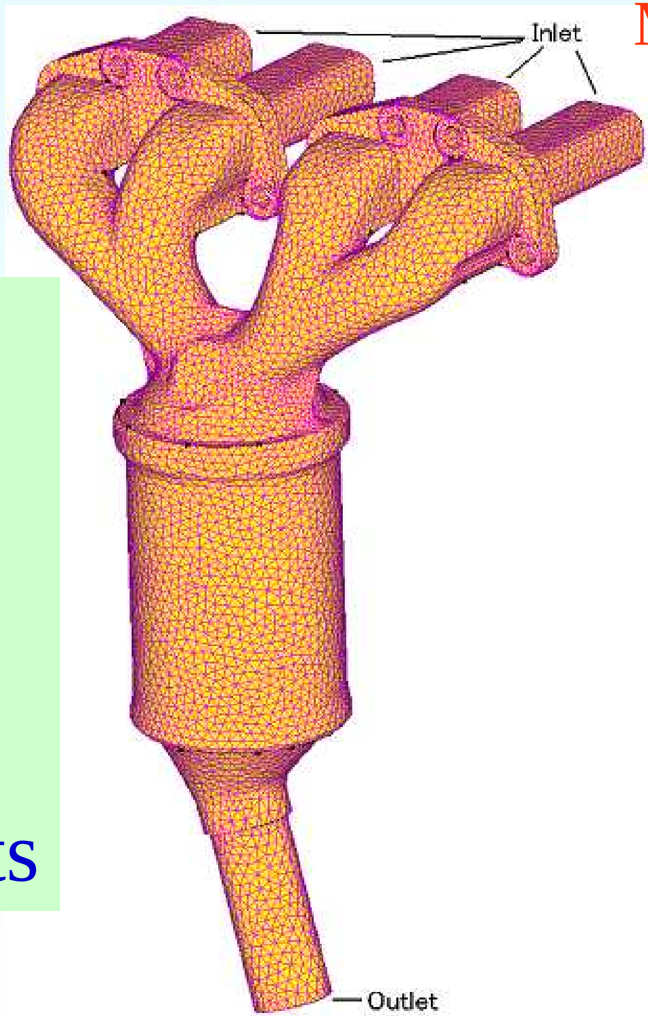
Using Solid part mesh and
temperature result to do
thermal stress analysis
ET 95

Volume Mapping

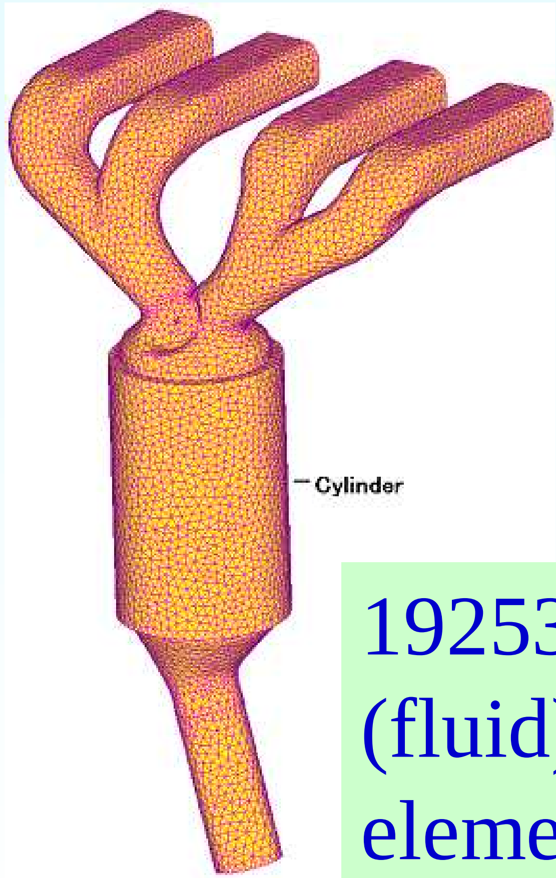
Transfer Solid temperature to A
finer mesh, and then to do
thermal stress analysis
ET 45,72,92,95

Example of Exhaust Port

Mesh Model（right：fluid domain）

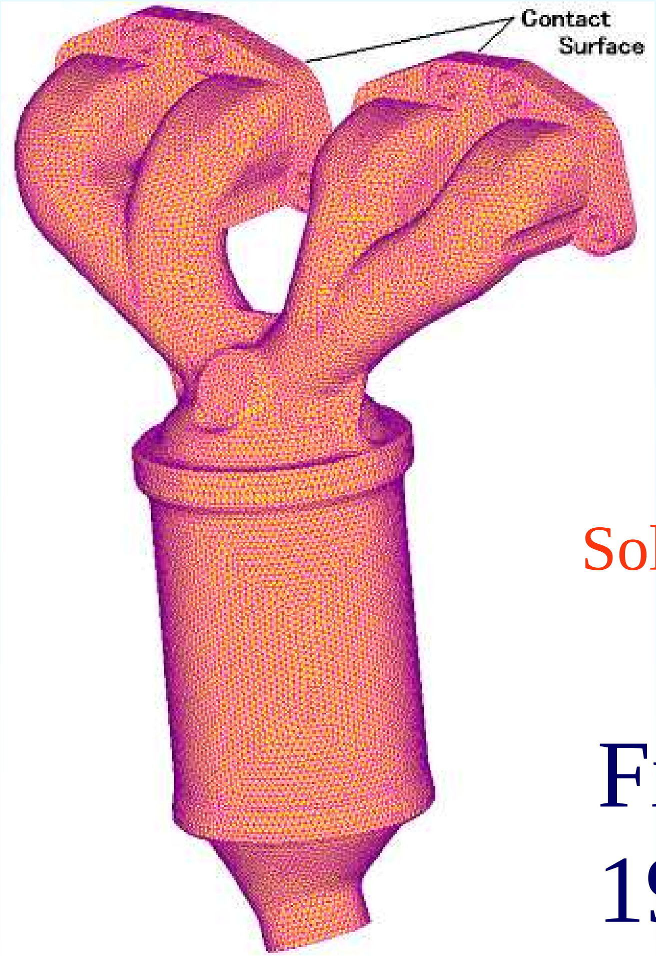


47566 (solid) + 192534 (fluid) elements



192534 (fluid) elements

Example of Exhaust Port



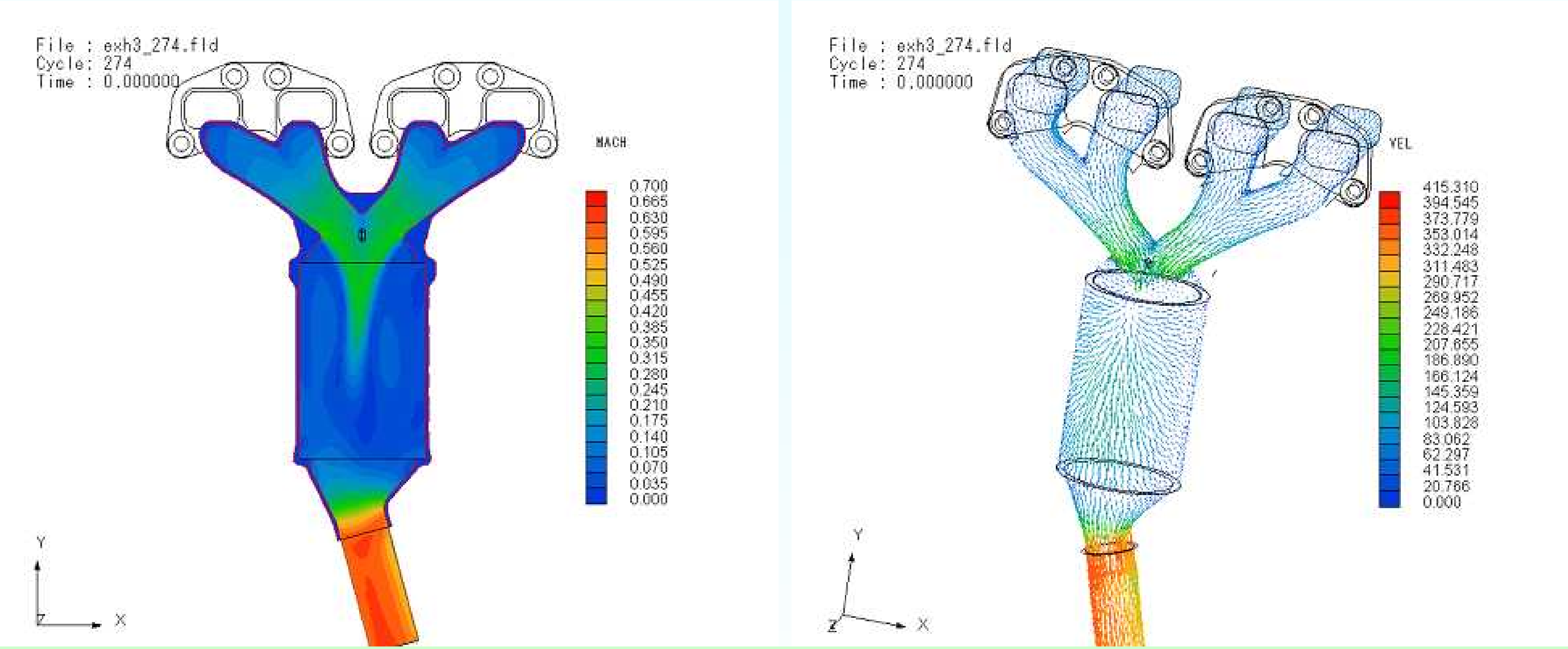
Solid Part FEM Model

Finer Mesh
198433(solid)

Calculation Conditions

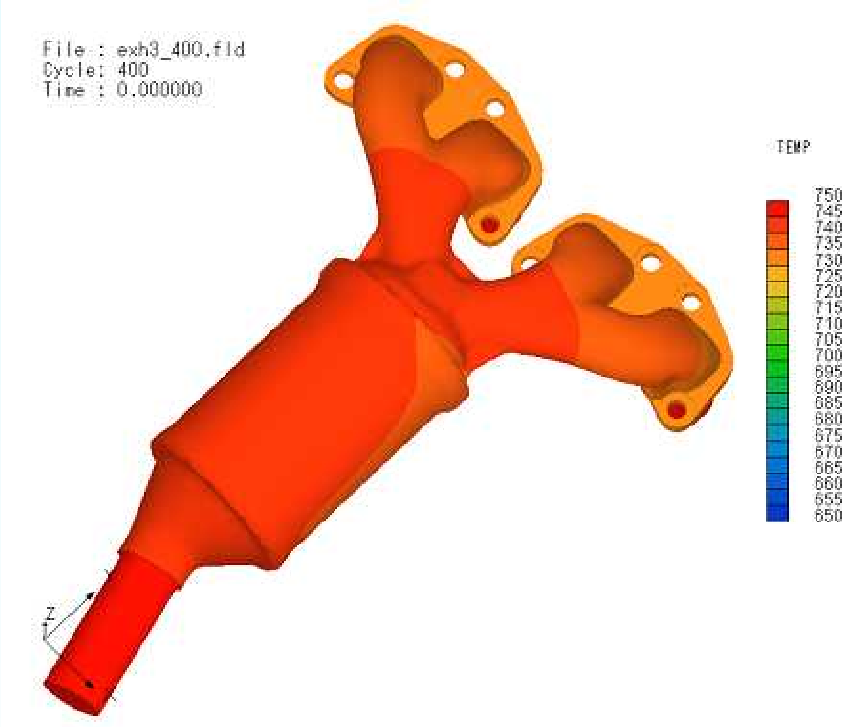
- mass flow rate at each inlet is 0.0628 kg/s
- inlet fluid temperature is 1023 K
- outlet pressure is 138.7 kPa
- filter condition is applied in the cylinder part
- film coefficient on the outer wall of the exhaust manifold is set to 2.9 $W/m^2 \cdot K$ and ambient temperature is set to 573 K
- node movements are fully constrained at two contact surfaces of the flange (last page)

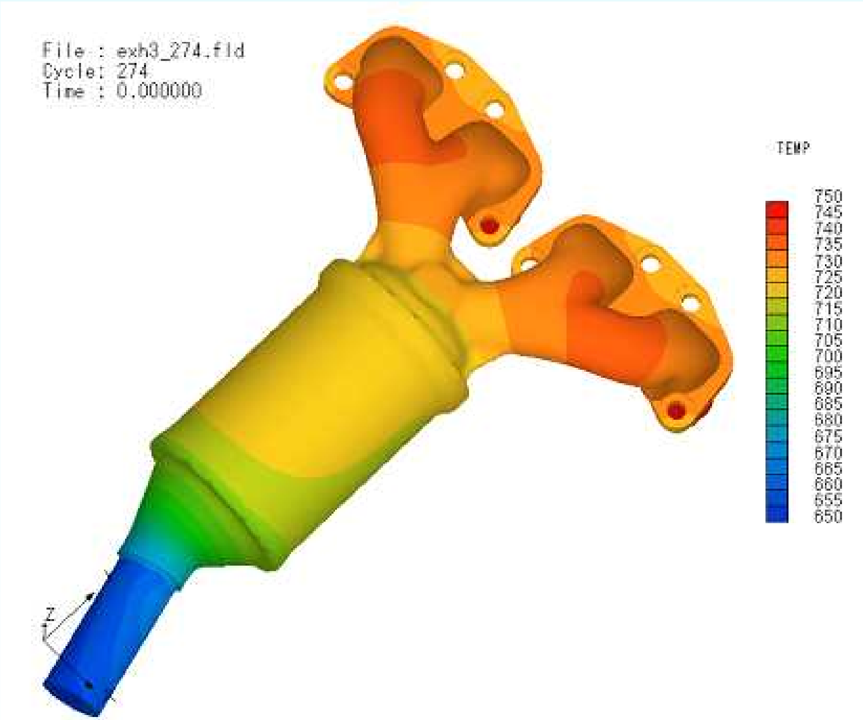
Calculation Results



air is treated as an ideal gas: Left: Contour plot of Mach number in the filter cylinder center cross section. Right: flow pattern.

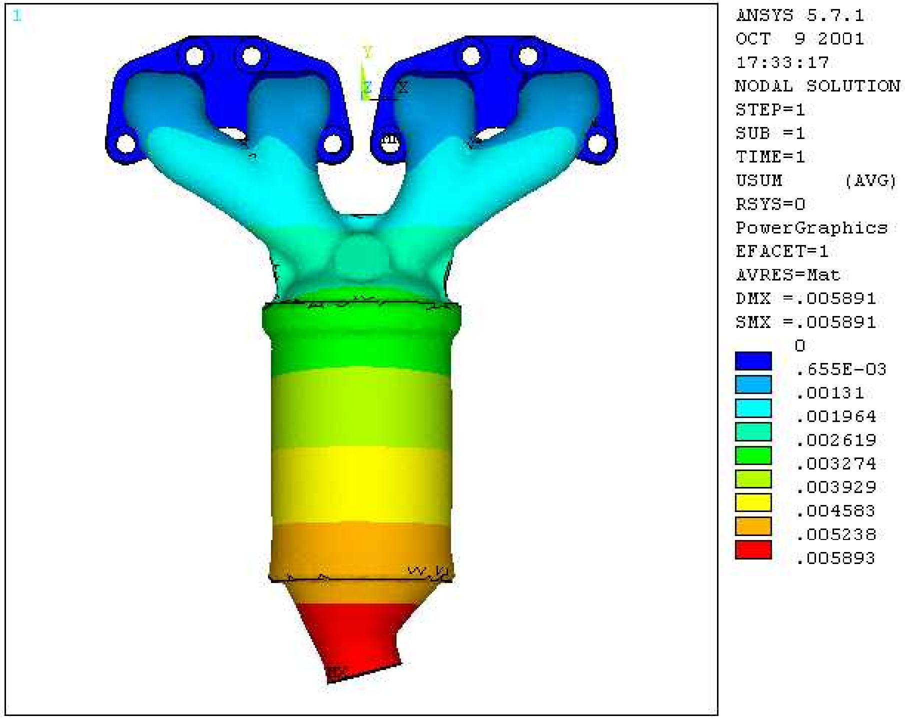
Calculation Results

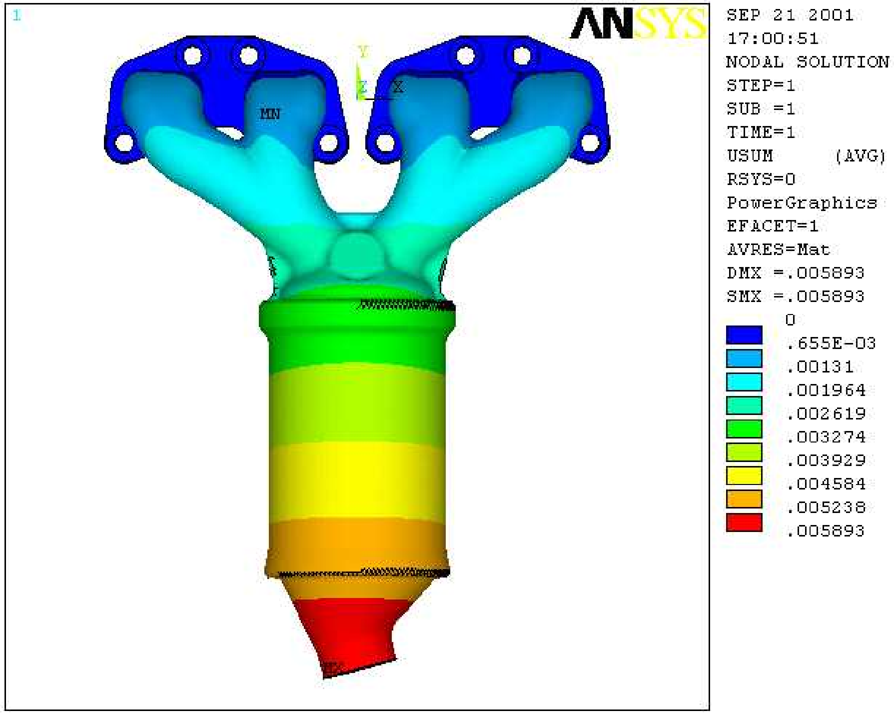




temperature distribution : Left: air is treated as an incompressible fluid. Right: air is treated as an ideal gas. Temperature scale is in centigrade.

Calculation Results





Displacement distribution of exhaust model:
Left: Direct conversion **Right:** Volume mapping

Calculation Results

	SC/ Tetra	ANSYS Element Type			
		45	95	72	92
Memory (Mbytes)	25	62	1516		
CPU Time (sec)	692	699	3152		

Table 3: Expected memory and CPU time requirements for a typical computational mesh containing 100,000 elements, CPU time for CFD is the time to advance 100 cycles. The CPU time is estimated using a PC with Pentium III 866 MHz CPU. Note that considerable deviation can result depending on the geometry, mesh quality, shapes of the elements used in the mesh and other factors.

Conclusions

- Even Mach Number M<0.7, compressible should be considered
- Conductivity can be used as constant
- The Volume Mapping for solid part temperature has priority
- The priority for choosing element should be 95,92,72

Conclusions

- The combination of SC/Tetra and ANSYS or other TSA is efficient, flexible and accurate.
- The volume mapping method is the favored method to couple CFD and thermal stress analysis
- Element 95 low order tetra and 45 tetra should be prohibited

Conclusions

- For ***Direct Conversion Method***, as one mesh is used in 2 stages of the whole analysis, there is no mapping and mapping error. But most thermal stress analyses use only one mesh shape, hybrid mesh is limited to use. In this case, a mesh generation with only tetrahedral in the solid part will make the coupling much easier.

When there is not mesh shape and memory limitation

Conclusions

- For ***Surface Mapping Method:*** Because it is possible to use a mesh that spans only the fluid part in the CFD stage and to use another mesh that spans only the solid part in the thermal stress analysis stage, there is no limitation of element shape. And this method can be used for a bigger mesh than that in method 1 and 3 with the same resource. In the reverse, a few iterations between stages might be necessary to obtain a converged solution and an accurate mapping is necessary to avoid the mapping error. Especially, the calculations must be divided into 3 stages (thermal flow analysis in flow part, thermal analysis in solid part and thermal stress analysis in solid part), they will take a bit more effort to do.

To divide the solid and fluid part into 2 mesh model to spare memory

Conclusions

- The ***Volume Mapping Method*** is most flexible to couple CFD and thermal stress analysis, but is less suitable than Surface Mapping Method for large-scale models.

Thanks For Your Attention!