JOINT INSTITUTE FOR NUCLEAR RESEARCH

Frank Laboratory of Neutron Physics, Sector of the new source and complex of moderators (Group №1 New neutron source)

FINAL REPORT
ON START Program

Pulsed Periodic Neutron Sources

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Contents

Abstract

The main objectives of the training are to identify the different types of the pulsed reactors and know their characteristics and uses, and learning how to perform basic computational fluid dynamics simulations by (ANSYS program) in order to conduct a thermal hydraulic analysis of reactor core.

The facility for assuring the generation of regulated and recurring bursts of nuclear fission is referred to as a PULSED REACTOR. In contrast to stationary nuclear reactors, which have a power level that is constant over time, pulse reactors generate brief power pulses and, as a result, neutron flux pulses. The pulses could be short -less than $10\ \mu s$ or long -more than $100\ \mu s$. The pulsed neutron sources are used mainly for neutron scattering experiments and useful for particular types of research, such as those that involve measuring a neutron's speed as it moves across a predefined distance.

ANSYS is a general-purpose, finite-element modeling package for numerically solving a wide variety of mechanical problems. These problems include static/dynamic, structural analysis, heat transfer, and fluid problems, as well as acoustic and electromagnetic problems.

Introduction

Nuclear reactors are used as research tools, as radioisotope production systems, and most prominently as energy sources and neutron sources.

There are several types of nuclear reactors that can be classified into thermal, resonance and fast neutron reactors. Nuclear reactors also can be classified according to its purpose, Moderator type, Coolant, Core Construction, Reactor Construction and Power Production.

One of the most important types of reactors that I will focus on is the Pulse Reactor. A Pulsed Reactor is a device that ensures the production of controlled, recurrent bursts of nuclear fission. Pulse reactors produce brief power pulses and, as a result, neutron flux pulses, in contrast to stationary nuclear reactors, which have a power level that remains constant throughout time. Less than $10\ \mu s$ pulses or longer than $100\ \mu s$ pulses are both possible. The pulsed neutron sources are beneficial for specific types of study, such as those that entail monitoring a neutron's speed as it travels across a preset distance. They are mostly employed for neutron scattering experiments. Pulses reactors can be classified into several types

1. Types of Pulses Reactors

1.1. Pulsed Aperiodic reactor, in which the fission burst is initiated by the rapid insertion of excess reactivity with transition of the reactor to the super critical state on prompt reactor, and which is quenched by negative temperature - reactivity feedback. In future, these reactors will be called burst reactors (abbreviation BR). Reactors of this type operate on both thermal and fast neutrons; the latter are called fast burst reactors - FBR.

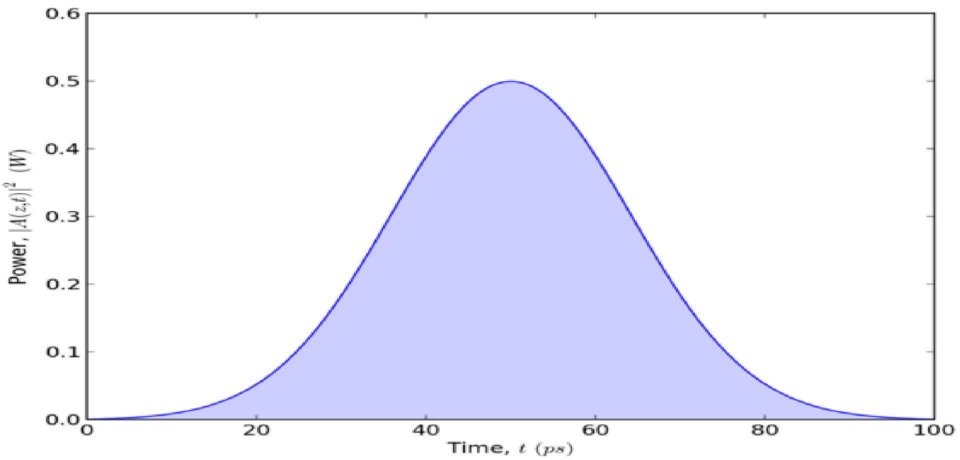


Fig 1. Power change in the Pulsed Aperiodic reactor

1.2. Pulsed Periodic Reactors (PPR), in which the fission bursts are formed entirely with external mechanical reactivity modulation and with a specified periodicity. Periodic pulsed reactors stand closer to reactors with a steady state flux than to fast burst reactors, in their thermophysical and dynamic properties.

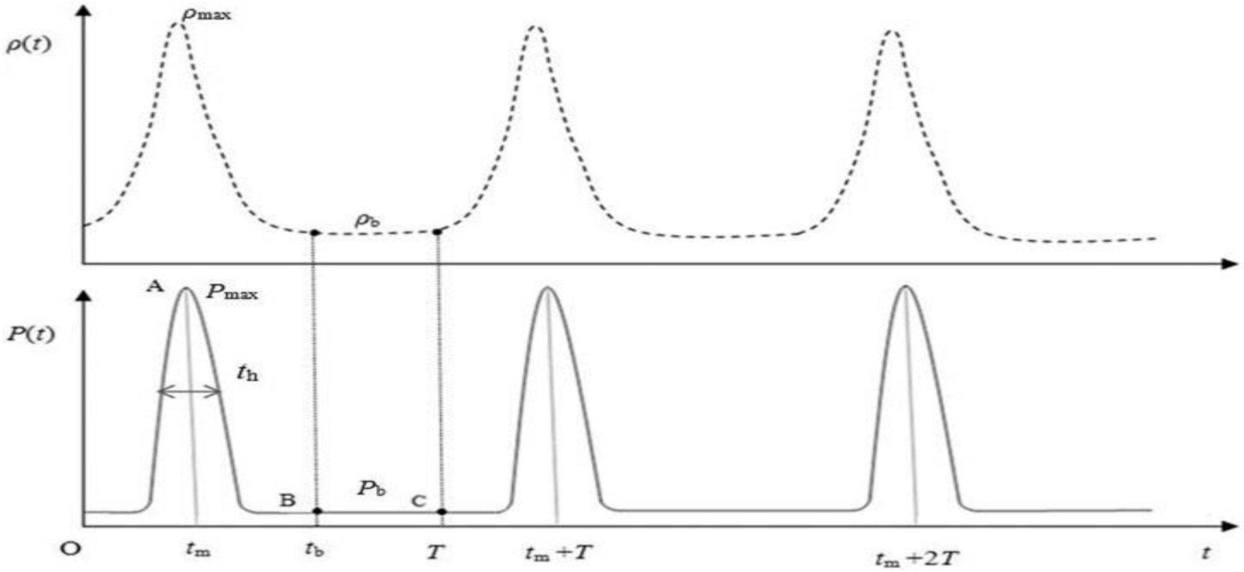


Fig 2. Power and Reactivity change in the PPR

1.3. Boosters, which are reactors existing in the subcritical state on prompt neutrons, and in which the power pulse is developed because of the multiplication of neutrons from an external pulsed source (periodic or aperiodic), mainly the targets of electron accelerators.

$$Booster = Periodic\ Pulsed\ Reactor + Accelerator(p, e),$$

Note:

- **1** high energy proton gives (20-40) neutrons after spallation;
- The energy obtained after spallation is equal to a **quarter** of the energy of fission.

And the main idea for pulsed reactor is to be as a neutron source.

2. History of pulsed reactors

The history of pulsed reactors started during the Manhattan Project when, at January 1945 under the direction of Otto Frisch, the first controlled prompt neutron fission chain reaction was achieved. The moving part of the reactor was raised by of an electromagnet in the upper part of a girder of height about 6 m, and the fixed part of the core rested at the base of the girder. When the electromagnet was switched off, a piece of uranium descended from above, slid along the guides and, with a velocity close to free - fall velocity, passed through the core close to its center. The weight of the assembly was so adjusted that the maximum value of the multiplication factor, allowing only for the contribution from prompt fission neutrons, was greater than unity.

According to the shape of the neutron pulse, which was developed during the flight of the moving part past the fixed part, the experimenter could estimate the lifetime of the fission neutrons. These experiments, with the light touch of the ingenious R. Feinman who compared them metaphorically with "tickling the tail of the sleeping dragon", received the conventional designation of "Dragon" compared them metaphorically with "tickling the tail of the sleeping dragon", received the conventional designation of "Dragon".

" The majesty of its occurrence " gave impetus to the creation of a large series of fast neutron pulsed reactors, generating power pulses on another principle by the self - quenching of the fission reaction. In 1952 in the Los Angeles Scientific Laboratory

(USA), an unplanned runaway of the " Jemima " prompt neutron " bare " uranium assembly occurred. The energy of the accidental burst was $1.5 \cdot 10^{16}$ fissions.

Neither part of the assembly came to any harm, nobody was irradiated, and no discharge of radioactive products occurred. This precedent revealed the self - quenching property of small metal assemblies and stimulated the modification of the already existing Godiva - I assembly (“Lady Godiva “) for the production of short, powerful neutron bursts. This mode of operation of a reactor is reminiscent of a miniature nuclear explosion and is very convenient for studying radiation damage and the nature of irradiation of a locality. But the FBR has been used not only for military purposes. The small duration of the pulse of a self - quenched fast neutron reactor, in conjunction with the high intensity, has opened up an extremely broad field of applications, as a source of neutrons and y - quanta for the investigation of short - lived radioactive isotopes, rapidly - changing radiation damage in materials, electronic components and biological units. Because of their small size, FBR are very suitable for the irradiation of samples of any size in the external radiation field. Highly accurate experiments are possible because of the excellent reproducibility of the reactor power bursts.

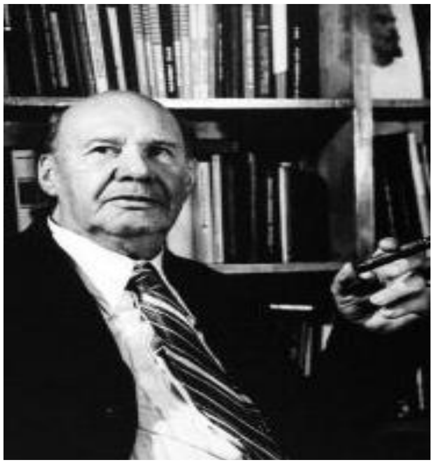
3. The history of the Pulsed reactors in Dubna

In late 1955 in the Institute of physics and Power Engineering in Obninsk Russia, a seminar was held where the American scientists work devoted to the investigation of the neutron energy dependency of uranium-235 fission cross section was discussed.

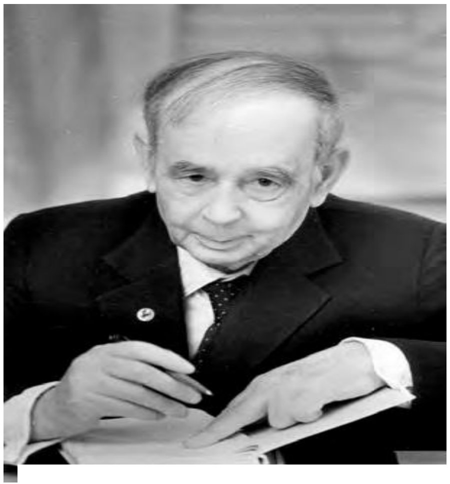
In the experiment that use a disc with a thin layer of uranium on its surface with it was rotating simultaneously with the beam chopper, they measured the radioactivity which appeared at the rim of the disc, suddenly Russian physicist Dmitri Ivanovich Blokhintsev raised his hand and asked why not fix a part of the reactor active zone on a rim of such the disc so that each revolution this part passes near the stationary zone and creates a super critical mass for a short time.

Hence, physicists from Obninsk (Russia) under the direction of D.I. Blokhintsev proposed to build a new type of nuclear reactor "fast pulsed reactor (IBR)" of periodic operation, which generated neutrons in pulses at a pulse frequency necessary for conducting experiments.

3.1. IBR-1



D.I. Blokhintsev (1908 – 1979)



I.M. Frank (1908 – 1990)

F.L. Shapiro (1915 – 1973)

Its design was simplistic as it operated at a fairly small average power of 1 kW (but the instantaneous power per pulse reached 5 MW) Later, it was demonstrated that the average reactor power could be raised to 6 kW with increased cooling air consumption, and since 1964 the reactor has been operating with a power of 2 to 6 kW.

In general, rather long pulse of the reactor $(5 - 50\,\mu s)$ was more adequate to the tasks of condensed matter physics and frequency of (5-50) HZ.

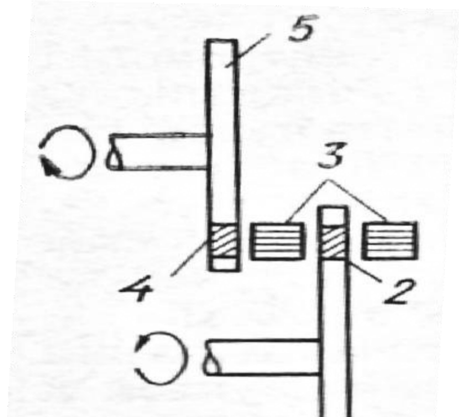


Fig 3. Schematic diagram of IBR
1 – reactivity modulator disk;
2 – uranium insert (main movable core); 3 – two parts of plutonium core, 4 – uranium insert (additional movable core); 5 – additional reactivity modulation disk.

3.2. IBR-30 reactor with an injector (Super Booster)

The average power of the first IBR reactor was initially low – 1 kW, later 6 kW. However, the peak power at a repetition rate of 8 pulses per second amounted to 3 and 18 MW, respectively, while in the mode of rare pulses (once every 5 s) it was up to 400 MW. In 1968, IBR was shut down, and a new reactor of the same type (IBR-30) with an average power of $25\,kW$ took its place in 1969. The flux of thermal neutrons in the pulse amounted to ($10^{14}\ \frac{n}{cm^2 \cdot s}$). However, the relatively long pulse of $60\,\mu s$ provided a resolution 60 times lower than it was required.

In 1969, a more powerful linear electron accelerator with a pulse current of $200\,mA$ and pulse duration of about $1\,\mu s$ was installed in place of the microtron. A tungsten target was placedin the reactor core (I.M. Frank, Particles and Nucleus, v. 2, N 4, 1972). Until 1996, the IBR-30 reactor operated in two modes: as a pulsed reactor and pulsed super booster. From 1996 and until 2001 the IBR-30 operated only as a booster-multiplier with a pulse frequency of 100 pulses per second, an average power of the multiplying target of $12\,kW$, and a pulse half-width of $4\,\mu s$.

3.3. IBR-2M Reactor

IBR-2 is a pulsed fast reactor of periodic operation. Its main difference from other reactors consists in mechanical reactivity modulation by a movable reflector.

The movable reflector is a complex mechanical system providing reliable operation of two parts, which determine the reactivity modulation: the main movable reflector and the auxiliary movable reflector.

The rotors of the main and auxiliary movable reflectors rotate in opposite directions with different velocities (1500 and 300 revolutions per minute). When both reflectors coincide near the reactor core, a power pulse was generated (1500 MW).

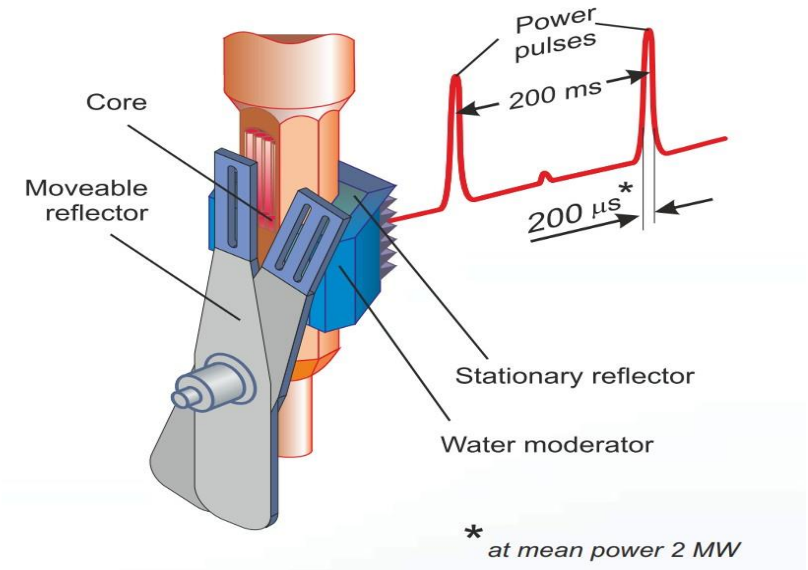
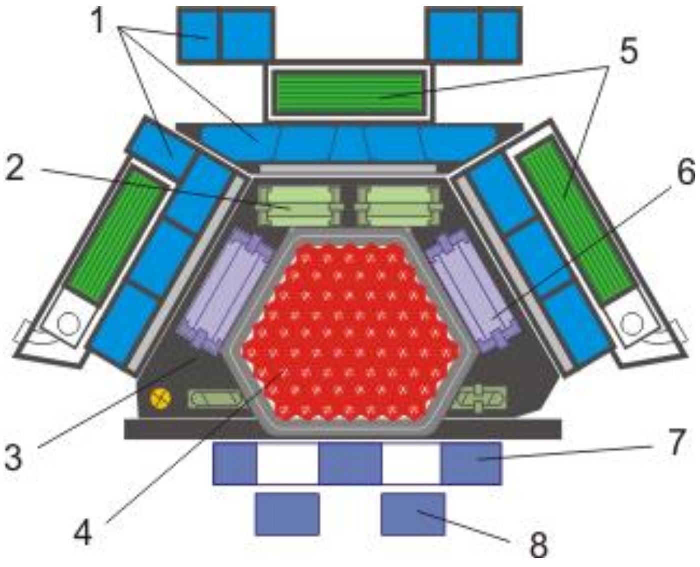


Fig 4. IBR-2M Reactor



1 - Water moderators, 2 - Safety system, 3 - Stationary reflector, 4 - Fuel assemblies, 5 - Cold moderators, 6 - Control rods, 7 - Main movable reflector,8 - Auxiliary movable reflector

Fig 5. Reactor Core

Fuel elements are composed of plutonium dioxide pellets and have a central hole, which allows an increase in the feasible burnup depth by a factor of 1.5.

Table 2. Parameters of IBR-2

Name	**Value**
Average power, MW	4
Fuel	PuO_2
Number of fuel assemblies	69
Maximum burnup, %	9
Pulse repetition rate, Hz	5; 10
Pulse half-width, µs: fast neutrons thermal neutrons	 200 340
Rotation rate, rev/min: main reflector auxiliary reflector	 600 300
MMR and AMR material	nickel + steel
MR service life, hours	55000
Source of spontaneous fission	Contains 0.43 $\mu g\ of\ {}^{252}_{98}Cf$
Moderator	Ordinary Water (H_2O)and mixture of mesitylene (C_9H_{12}) and meta-xylene ($C_6H_4(CH_3)_2$)

4. Neutron Moderator

Neutrons generated from fission in reactor's core have a high energy "about 200 MeV", so to use them in different experiments, they must undergo a moderation process to reduce neutron's energy to thermal or cold one. So, we use a neutron moderator next the reactor core for this purpose. Hydrogen containing materials like Ordinary Water (H_2O)and Mesitylene (C_9H_{12}) are used as a neutron moderator.

4.1. Requirement of the Neutron moderator

i. Large scattering cross section;
ii. Small absorption cross section;
iii. Large energy loss per collision.

- **Average logarithmic energy decrement, $\boldsymbol{\xi}$**

$$\xi = ln\, E_i - ln\, E_f = ln\frac{E_i}{E_f} \cong \frac{2}{A+\frac{2}{3}},$$

Whereas, E_i- Energy of neutron before one collision;
E_f- Energy of neutron after one collision
A- Atomic weight.

- **Number of collisions, N**

$$N = \frac{ln\, E_{high} - ln\, E_{low}}{\xi},$$

Whereas,
E_{high}, Energy of neutron at the beginning;
E_f, Energy of neutron at the end.

- **Macroscopic Slowing Down Power "MSDP"**

$$\text{MSDP} = \xi \cdot \Sigma_S,$$

Whereas, Σ_S- Scattering macroscopic cross section;

- **Moderation Ratio, MR**

$$MR = \frac{\xi \cdot \Sigma_S}{\Sigma_a},$$

Σ_a, Absorption macroscopic cross section.

5. Neutrons

Neutrons are used for studying fundamental symmetries and interactions, structure and properties of nuclei, but nowadays neutrons are mostly required in investigations of condensed matter including solid states, liquids, biological systems, polymers, colloids, chemical reactions, engineering systems, etc.

5.1. Classification of neutrons according to their spectra

Neutron flux spectrum represents the distribution of neutron energies within some medium.

Table 1. Classification of Neutrons due to Spectra

Name	Energy (E), eV	Wave Length(λ), Fm
Ultracold Neutrons	$[10^{-11} \to 10^{-7}]eV$	$\lambda = [\infty \to 1.5 \cdot 10^{7}]\ Fm$
Cold Neutrons	$[10^{-7} \to 10^{-3}]\ eV$	$\lambda = [1.5 \cdot 10^{7} \to 1.5 \cdot 10^{5}]\ Fm$
Thermal Neutrons	$[10^{-3} \to 0.5]\ eV$	$\lambda = [1.5 \cdot 10^{5} \to 6.5 \cdot 10^{3}]\ Fm$
Intermediate Neutrons	$0.5\ eV \to 0.1\ MeV$	$\lambda = [6.5 \cdot 10^{3} \to 15]\ Fm$
Fast Neutrons	$0.1\ MeV \to 50\ MeV$	$\lambda = [15 \to 0.65]\ Fm$

6. ANSYS

ANSYS is a general-purpose, finite-element modeling package for numerically solving a wide variety of mechanical problems. These problems include static/dynamic, structural analysis, heat transfer, and fluid problems, as well as acoustic and electromagnetic problems.

Ansys simulation gives engineers the ability to explore and predict how products will work — or won't work — in the real world.

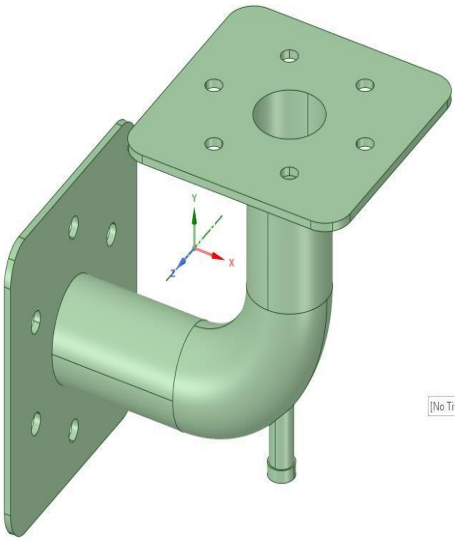
During this training, I have learned how to perform basic computational fluid dynamics simulations (CFD) on the basis of end-to-end workflow, starting with CAD models in ANSYS Space Claim, creating quality meshes with ANSYS Meshing, and all aspects of performing CFD simulations in ANSYS CFX.

6.1. workshop 1: Mixing Hot and Cold Streams in a Mixing Elbow

6.1.1. Problem Description

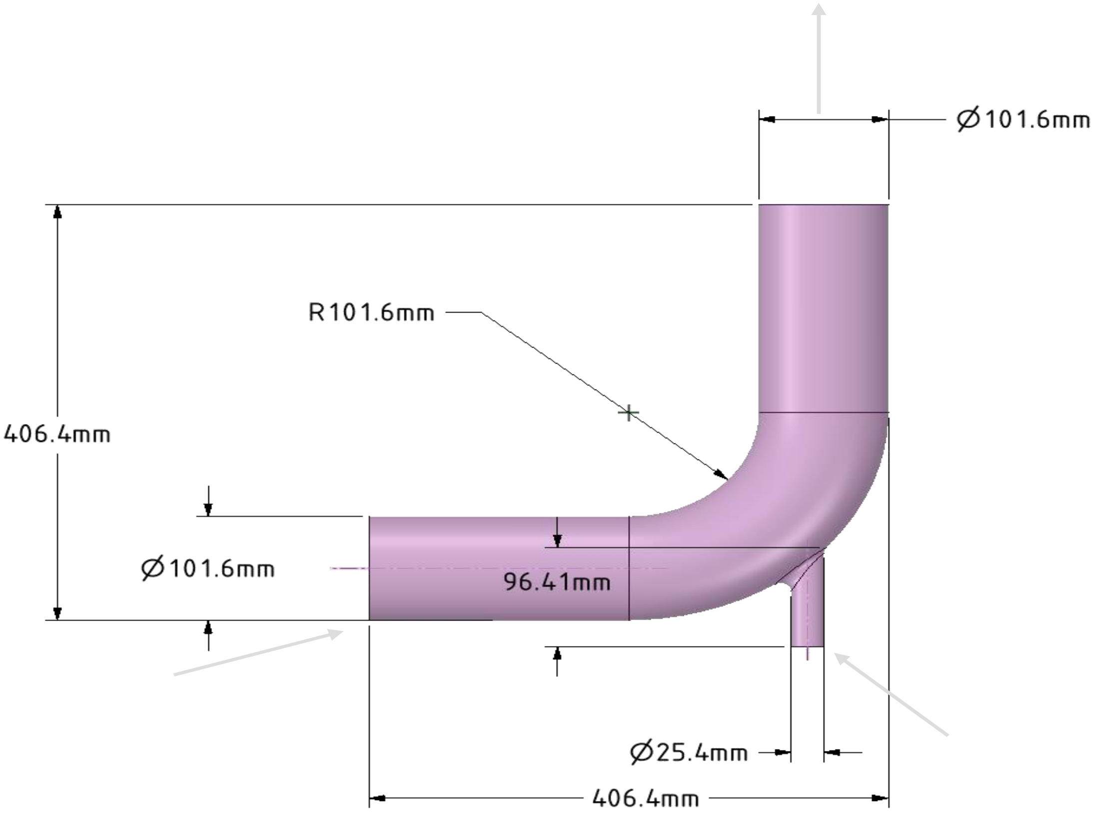
- Mixing of two or more fluid streams is a common process industry operation

- Streams may have different velocity, temperature, composition, …
  - Uniformity of the resulting flow is often desirable.
- In this problem a mixing elbow is used to mix two streams of water at different temperatures.
- The goal of the analysis is to determine whether the elbow design will produce good enough mixing under the current operating conditions to achieve a uniform temperature profile at the outlet.
- Simulation will predict the uniformity of the temperature across the outlet plane and the pressure drop that occurs in the elbow.



6.1.2. Geometry and Operating Conditions for Mixing Elbow

- Outlet gauge pressure $=$ 0 Pa;
- Walls, adiabatic (heat flux $= 0$);
- Water, $0.33\frac{\mathrm{m}}{\mathrm{s}} - 20\ °\mathrm{C}$;
- Water, $0.9\frac{\mathrm{m}}{\mathrm{s}} - 30\ °\mathrm{C}$.



6.1.3. Boundary Conditions

The next step is to create the boundary conditions. I created a cold inlet, a hot inlet and an outlet. The remaining faces will be set to adiabatic walls. Currently all external 2D regions are assigned to the mixing elbow Default boundary condition.

Each domain has an automatic default boundary condition for external surfaces. The default boundary condition is a No Slip, Smooth, Adiabatic wall. As you create new boundary conditions, those regions are automatically removed from the default boundary condition.

- **Large inlet**

This inlet will have a normal speed of 0.33 m/s and Static Temperature of 20°C;

- **Small inlet**

Set the Normal Speed will to 0.9 [m s^-1] and the Static Temperature, 30 [C].

- **Outlet boundary condition**

Relative Pressure to 0 [Pa];

This is relative to the domain Reference Pressure, which is 1 [atm] (set as default value in a previous slide).

- **Wall Boundary Conditions**

The default boundary condition, mixing elbow Default, comprises all the 2D regions not yet assigned to a boundary condition.

The default boundary type is an adiabatic wall, which is appropriate here. To check, double-click on wall and select the Boundary Details tab

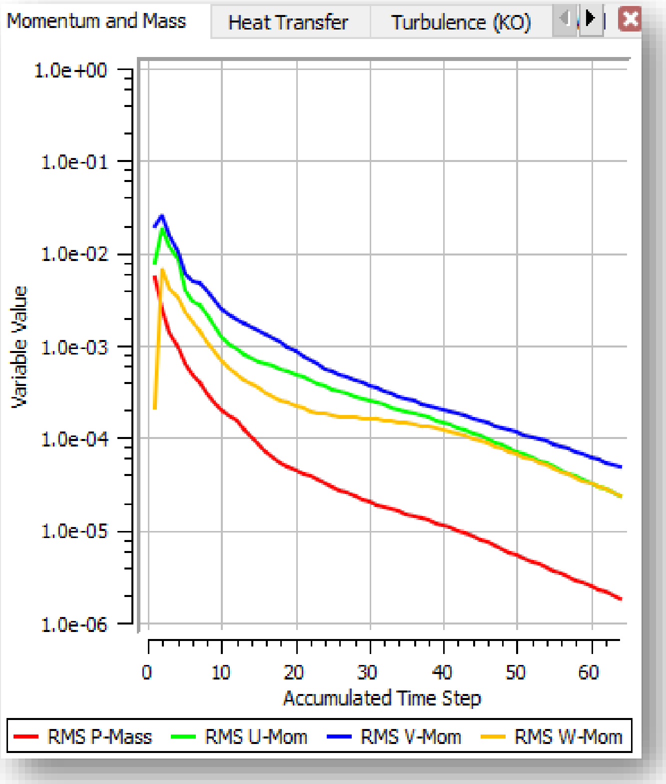
6.1.4. Solver Control

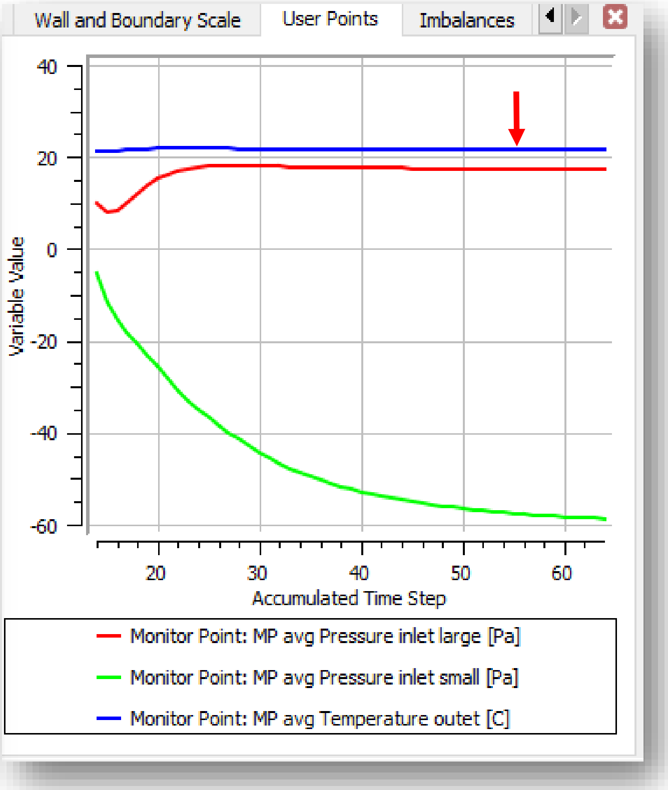
The Solver Control options set various parameters that are used by the solver and can affect the speed of convergence and the accuracy of the results. For this model the default settings are reasonable but will not be suitable for all simulations.

The solver stopped after Max. Iterations regardless of the convergence level.

6.1.5. Solution

Approximately 65 iterations are required to reduce the RMS residuals below the target of 1.0x10-4. The pressure monitor points approach steady values.

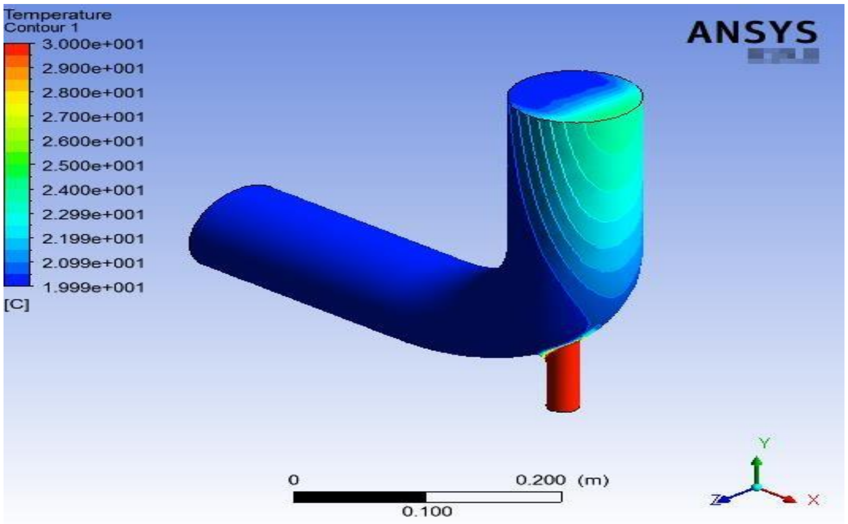




6.1.6. Post-processing Steps

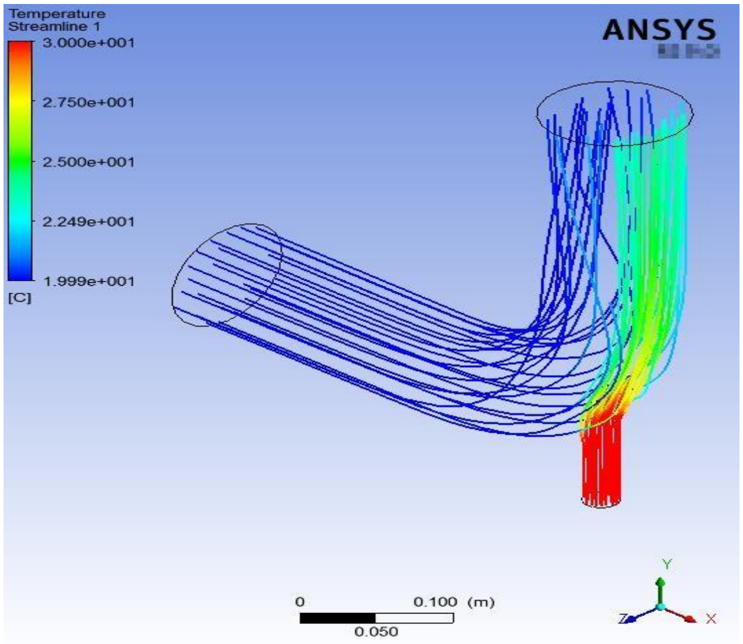
i. CFD-Post - Temperature contour plot

- ➢ A temperature contour plot on the walls and outlet is now visible.
- ➢ Outlet temperature profile is not uniform



ii. CFD-Post – Velocity streamlines

Note the complex, swirling flow pattern where the stream from the small inlet enters. It appears the temperature of this stream is reduced, as indicated by the green path lines, but the warm fluid does not mix further with the main stream by the time the outlet is reached.



6.1.7. Wrap-up

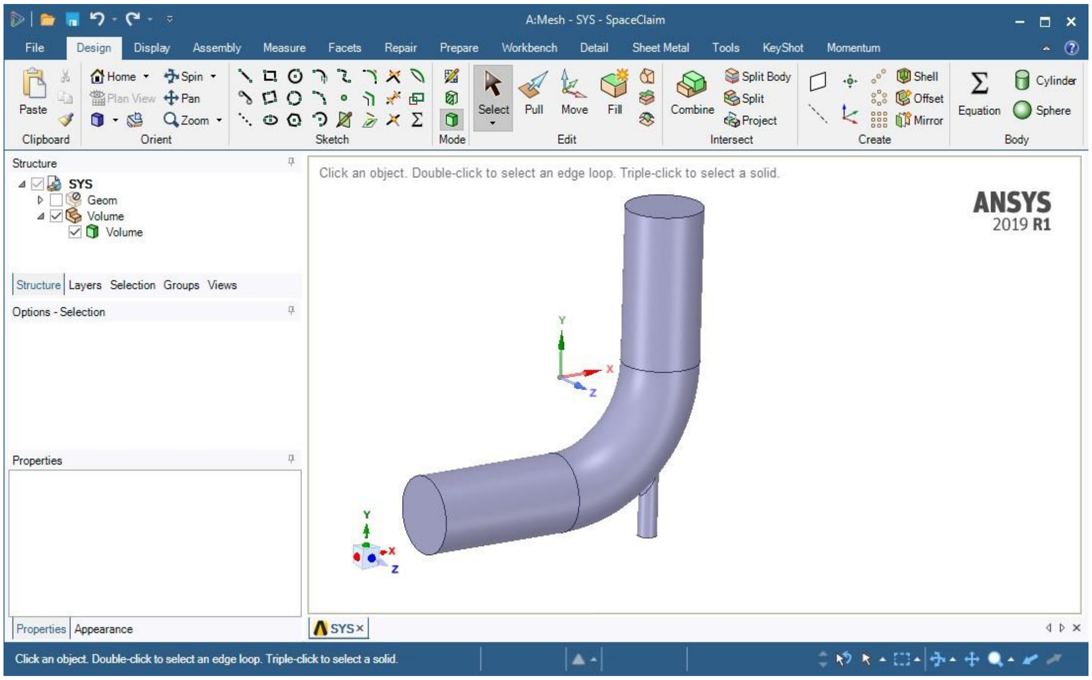
- This workshop has shown the basic steps that are applied in all CFD simulations:
  - Defining Material Properties
  - Setting Boundary Conditions and Solver settings
  - Running a simulation whilst monitoring quantities of interest
  - Postprocessing the results in CFD-Post
- One of the important things to remember in your own work is, before even starting.

6.2. The Second workshop in this course is “SOLVING”

6.2.1. Workshop Description

In this workshop I created a new mesh for the mixing elbow geometry, using planes, move and split operations in SCDM to decompose the geometry to create regions that are suitable for hexahedral meshing. I used the multizone method for sweep able bodies to create the mesh and then I performed the simulation with the new mesh to explore solution methods and solution controls.

6.2.2. Elbow Geometry

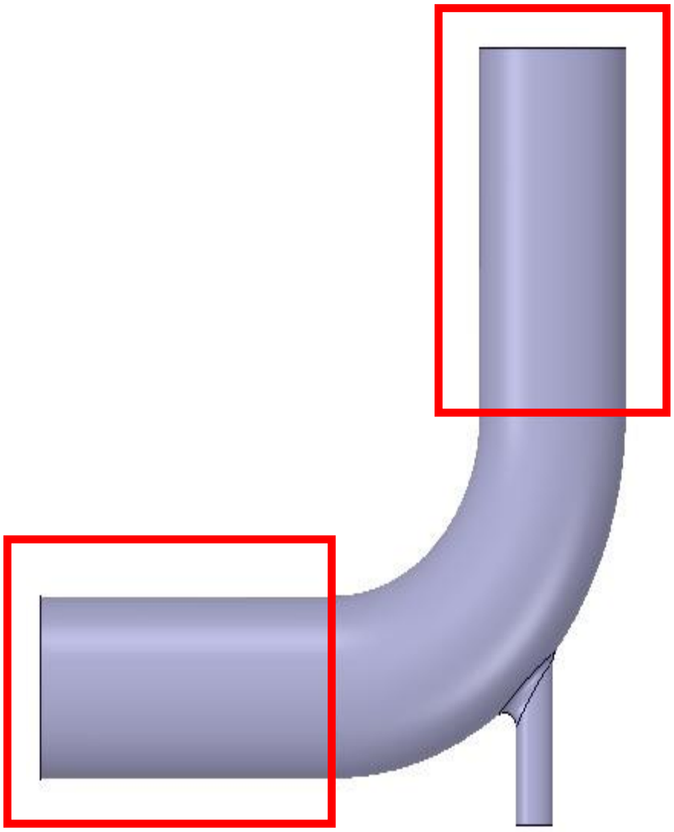


Click an object. Double-click to select an edge loop. Triple-click to select a solid.

Click an object. Double-click to select an edge loop. Triple-click to select a solid.

6.2.3. Slicing the body: Strategy

- In the previse workshop, we have seen that this geometry can be meshed with a combination of tetrahedral cells with inflation layers
  - This is a good approach for the region near the pipe intersection where there are complex surface intersections and curvature
- However, the straight pipe sections could easily be meshed with hexahedral cells, resulting in improved quality and reduced cell count
  - This is possible if the model is split into three parts
  - A few quick operations can split it into the two straight sections highlighted to the right, and the central, complex section.



6.2.4. CFD Solution

- The CFD Solution part of the workshop will contain two sections

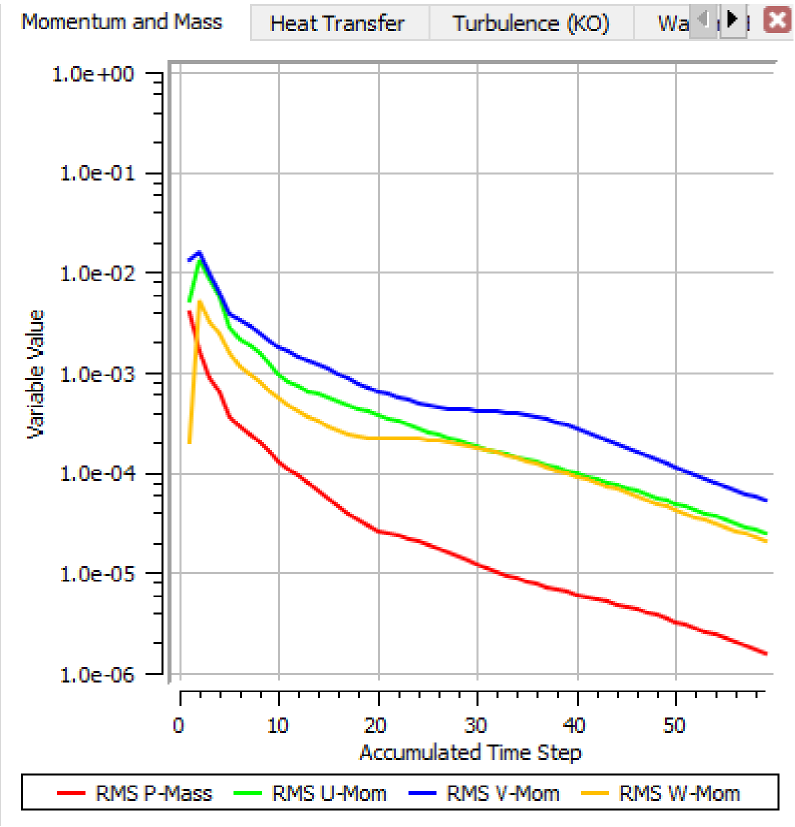
* Demonstration of why it is recommended to use the second order High Resolution Scheme for momentum and energy.

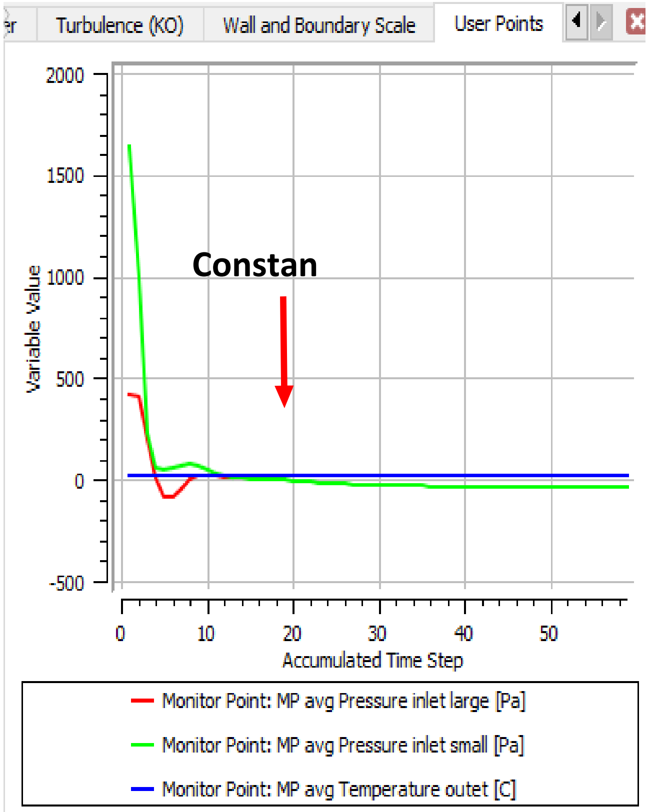
* Demonstration of what to do if the solution is not converging well.

Part 1: Discretization

6.2.5. Solving Solution

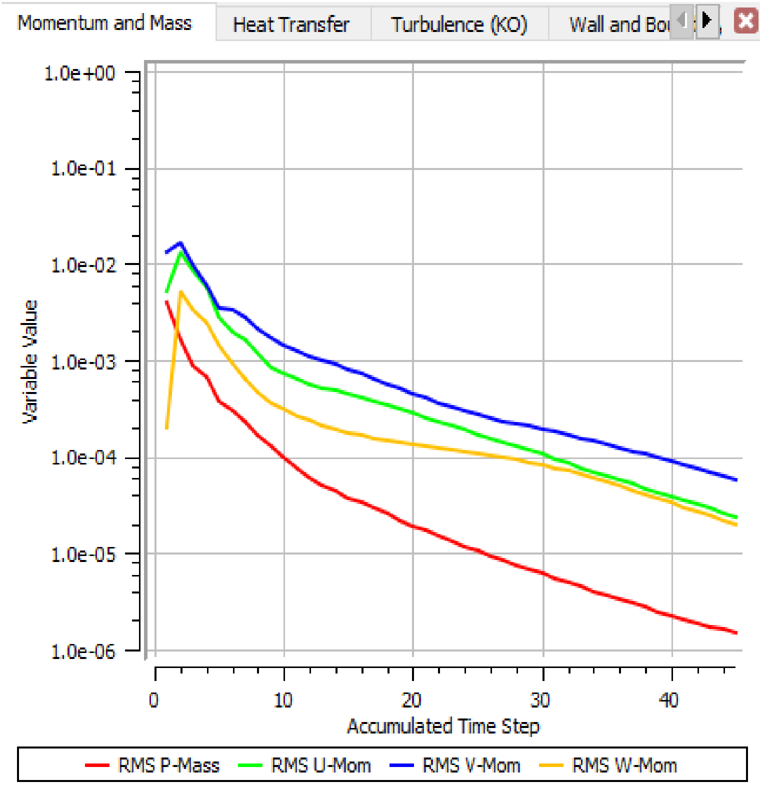
The convergence criteria for the residuals have been satisfied and the Monitor plots show that the solution is no longer changing.

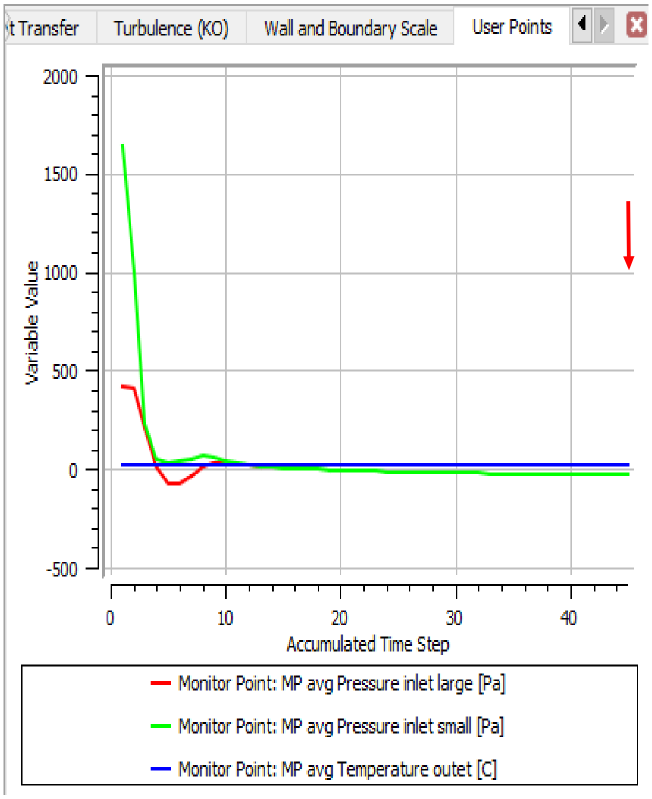




Changed the Advection Scheme Option form the default second order High Resolution to the first order Upwind scheme.

The purpose of this exercise is to emphasize why it is recommended to always use the second order High Resolution scheme for momentum and energy and also to illustrate how CFD results are affected by discretization.





6.2.6. Convergence of CFX system *First Order*

The convergence criteria for the residuals have been satisfied and the Monitor plots show that the solution is no longer changing.

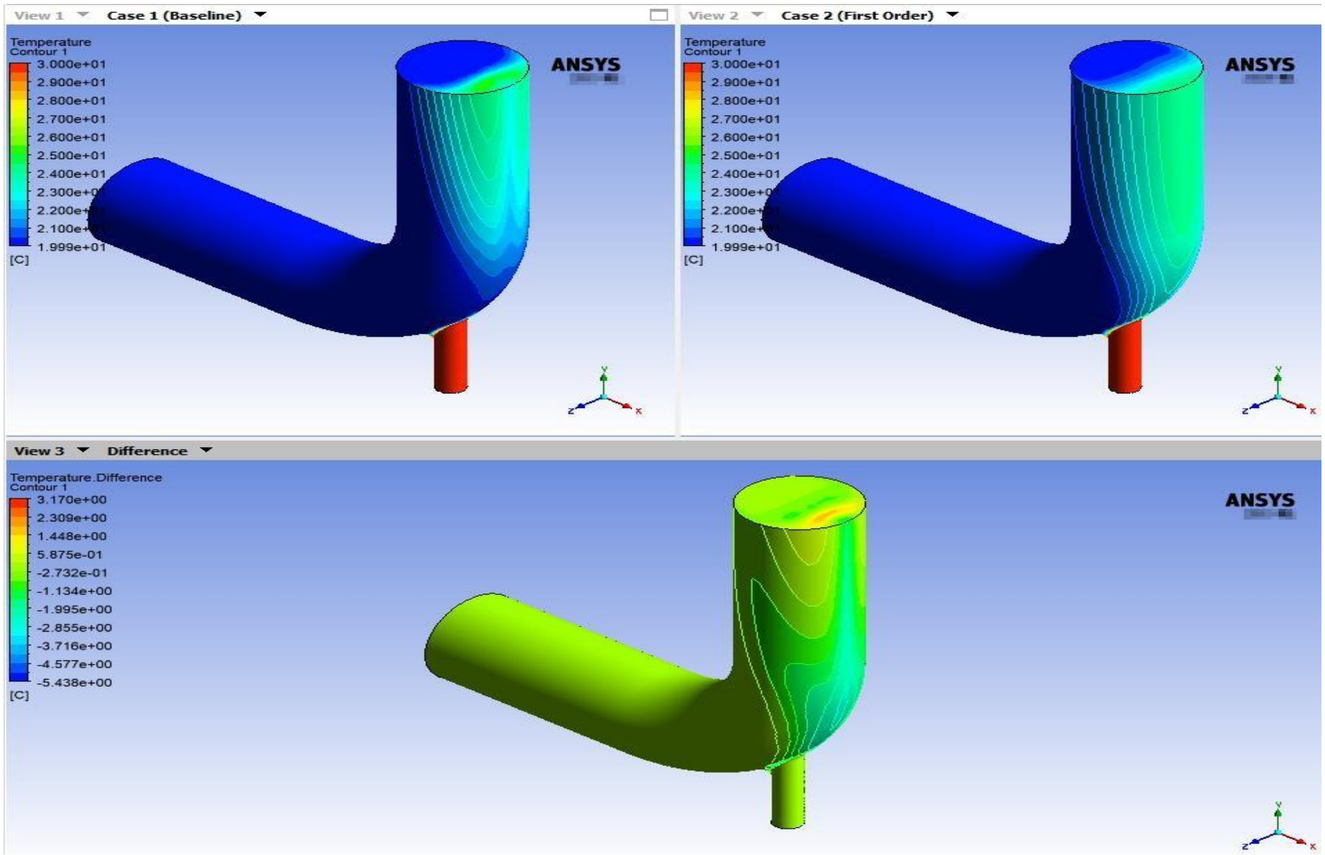
Note the solution converges faster than it did with second order high resolution scheme. This is typically the case because the first order discretization scheme is more diffusive and therefore usually easier to converge.

In some cases where it is difficult to converge using second order, a solution strategy that is used sometimes is to converge the solution with first order, then switch to second order and continue iterating until convergence is reached again.

- **CFD-Post will be used to compare results**

6.2.7. CFD-Post: Display Temperature Contour on Outlet

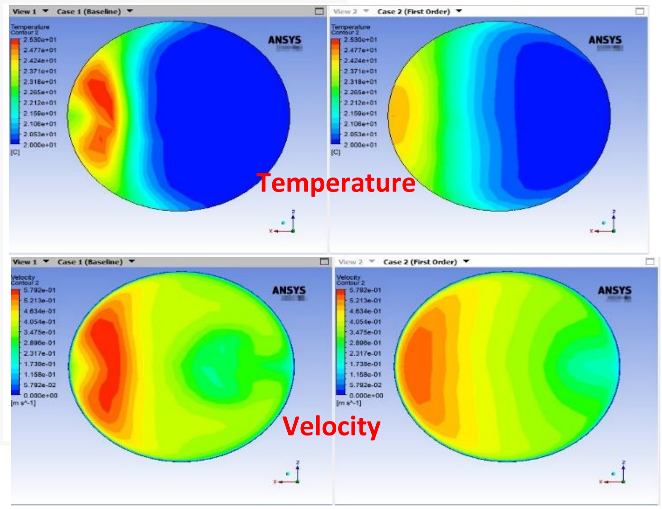
- With the settings of previous slide, CFD- Post will show any active graphical object (Contour 1 in this example) for both cases.
- The difference of the plotted variable is also shown at the bottom View.
- Cameras are synchronized in all 3 windows.



6.2.8. Discussion of Discretization

This exercise demonstrates why the use of first order upwind is not recommended. In some cases, it might be easier to get a converged solution, but that solution will generally be unreliable (inaccurate), as seen in the outlet temperature profiles.

In theory, if the grid resolution was made infinitely fine, first and second order solutions would be the same. In real life,



however, the grid is never infinitely fine so you should always keep the default second order high resolution discretization for momentum andenergy.

I have noticed that the turbulence equations donot use second order by default, but unlike momentum and energy, convection is rarely the dominant term in those equations so the effect of firstversus second order is often a secondary effect for turbulence models.

6.2.9. Summary

In this workshop I learned:

- How results can be affected by the use of different discretization schemes and why second order upwind should always be used for momentum and energy
- Strategies for diagnosing and overcoming convergence and unrealistic results problems.

7. Conclusion

During this training, I got acquainted with pulsed reactors and the most important types that are not found in the whole world except in Dubna, how they work and their importance as a source of neutrons. I used the Ansys software to analyze the temperature and velocity distribution inside the mixing elbow and learned Ansys and how to use it to analyze the reactor core thermal hydraulics [1-12].

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