



Numerical Investigation of The Immersion Liquid Blanket as a heat extractor in ARC Fusion Reactor

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Outlines

1. Introduction.
2. Comparing between immersion liquid and solid blankets from heat transfer point of view.
3. Effects of magnetohydrodynamics on FLiBe.
4. Heat exchanger for ARC blanket.
5. Acknowledgement.

1. Introduction

- The fusion reactions theory was developed in the 1920s and 1930s.
- There is several significant challenges in technology led to delaying its presence in the global energy system.

1. Introduction

- The fusion fuel must be at the plasma state. The temperature of the fusion fuel must be raised to approximately **200 million degrees Celsius**.
- The energy is produced within the plasma by nuclear reactions when magnetic confinement uses magnetic fields to retain plasma heat and to control plasma movement.
- Creating, maintaining, and manipulating at such a high-temperature plasma are distinctive scientific challenges.

1. Introduction

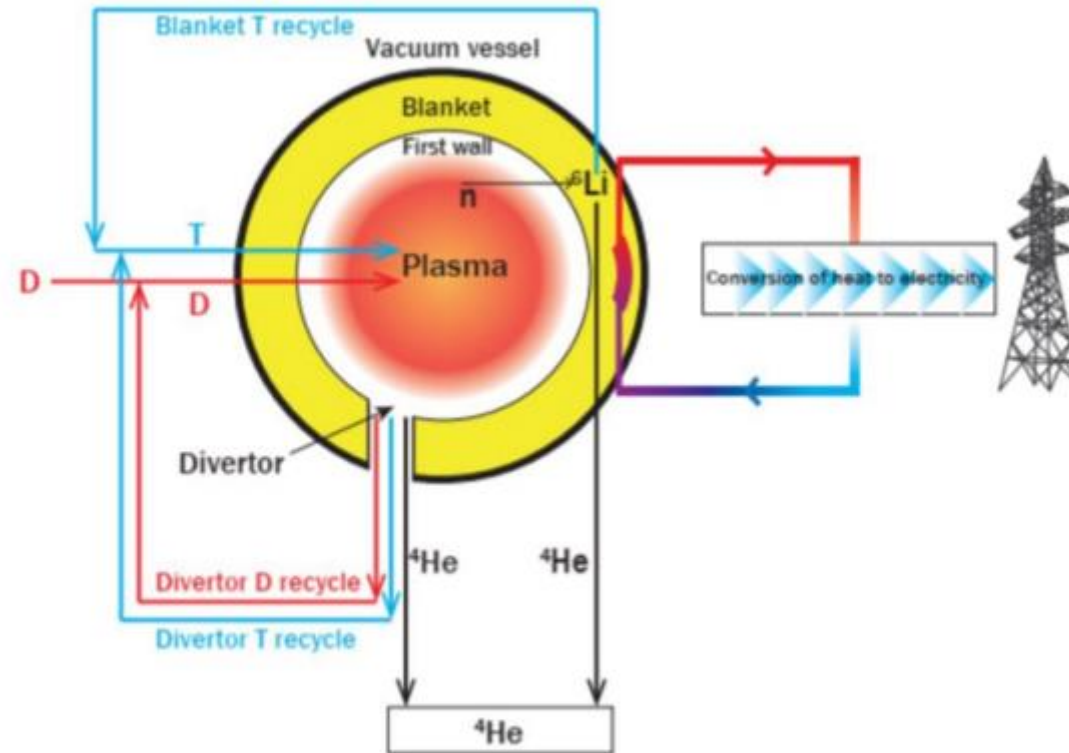


Figure 1.1: Schematic of materials flow through a fusion reactor system

1. Introduction

Traditional tritium breeding and neutron absorbing blankets:

- The blanket is generally contained within the TF coils, these structures must also be separable into toroidal sections.

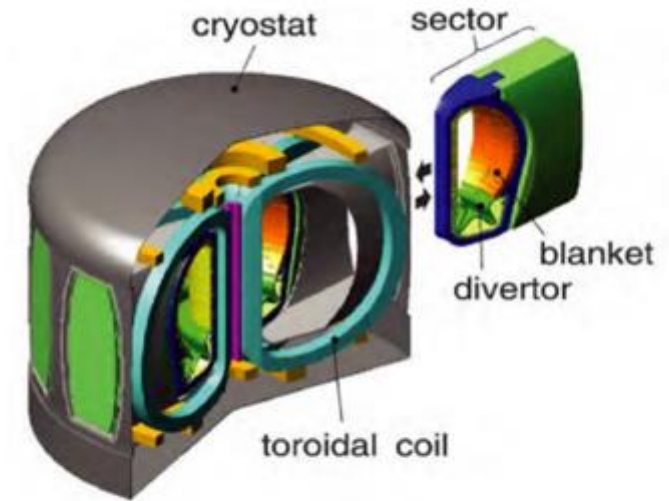


Figure 1.2: Toroidal sectors in a traditional tokamak

1. Introduction

- This leads to:
 - I. Challenging engineering constraints.
 - II. difficult remote handling.
 - III. Low tritium breeding ratio (TBR) as the structural part of the blanket does not usually contribute to breeding.

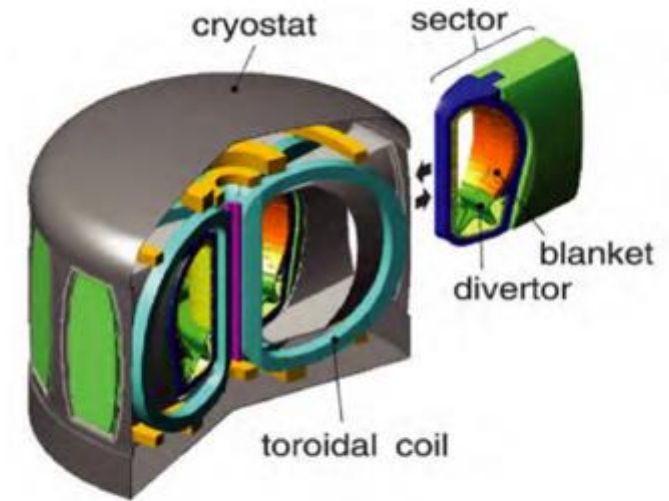


Figure 1.2: Toroidal sectors in a traditional tokamak

1. Introduction

Here some blanket designs which are briefly explored:

- For solid blanket fusion reactor: ARIES-I
- For immersion liquid blanket fusion reactor: ARC

1. Introduction

- ARIES-I blanket uses 10 MPa helium as coolant.

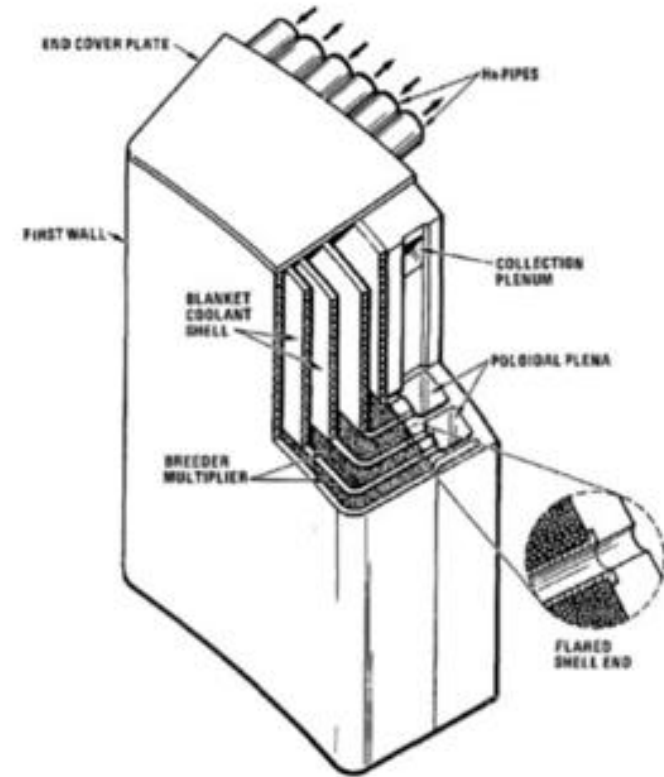


Figure 1.3: ARIES I blanket uses helium as coolant

1. Introduction

- Low volumetric heat capacity is the limitation of gas cooled design which requires very high pressure of the coolant.
- It leads to think of mixing solid particles with the stream than that of pure gas at the same pressure.

1. Introduction

Despite of mixing particles with a stream gas has enhanced the volumetric heat capacity, there were a lot of concerns about it like:

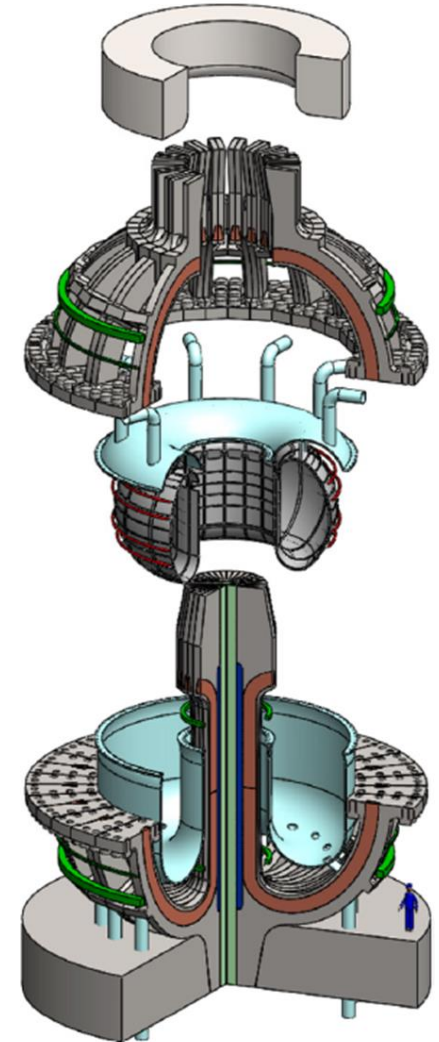
I. **Erosion** concerns.

II. Possibility of formation of **hotspots**, if particles settle in sharp corners.

III. **Engineering complexity** of designing the circulation system.

1. Introduction

- Several innovations are being used in ARC like :
 1. using FLiBe immersion liquid blanket.
 2. using high temperature superconducting (HTS) coils of rare earth barium copper oxide (REBCO)
 3. have joints enabling quick replacement of vacuum vessels.



1. Introduction

The used Software:

I. SOLIDWORKS

II. ANSYS

III. MATLAB

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Model description:

Fusion Reactors	ARC	ARIES I
Structural Material	FLiBe	SiC composite
Coolant		High pressure helium
Tritium breeder		Li_2ZrO_3
Neutron Multiplier		beryllium-metal sphere pellets
Approximation	Simplified models are used to deal with future mesh generation and computational hardware limitations related to S.S., 3D, turbulent flow which require very fine meshes at boundary layers.	
Simulated model	The simulations are run over 1/9 of the total blanket to deal with fine meshes problem and compensating for the whole blanket by using symmetry boundary conditions.	The blanket is simulated as vertical helium pipes with height 6.6m and radius 10cm.

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Governing Equations:

Heat Transfer Equations

- Continuity equation: $\nabla \cdot \vec{V} = 0$ (1)

- Navier-Stokes equations: $\rho \frac{d\vec{V}}{dt} - \nabla P + \rho \vec{g} + \mu \nabla^2 \vec{V}$ (2)

- Differential convection equation: $\rho c_p (\vec{V} \cdot \nabla) \vec{V} = K \nabla^2 T + \mu \Phi$ (3)

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

- Sensitivity Analysis is established by using several meshes and turbulence models for each cooling blanket.
- Three turbulence models **standard k- ϵ** , **realizable k- ϵ** , and **SST k- ω** with scalable wall function are used to compare solutions and show the solution dependency on the turbulence models.
- **SIMPLE algorithm** has been used for all simulations as it shows very good solution convergence.

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

1. Immersion liquid blanket:

Points to be displayed	Strategy
The dependency of the solution on mesh element size	By using 3 meshes of 141601, 305358, and 675987 elements.
Outlet temperature dependence on inlet flow.	By holding volumetric heating constant at 1.1 MW/m ³ and changing flow rate .
Outlet temperature dependence on volumetric heating	By changing volumetric heating from 1.1 to 2 MW/m ³ at <u>flow rate</u> of 0.89 m ³ /sec.
Heat exhausted dependence on volumetric heating	

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

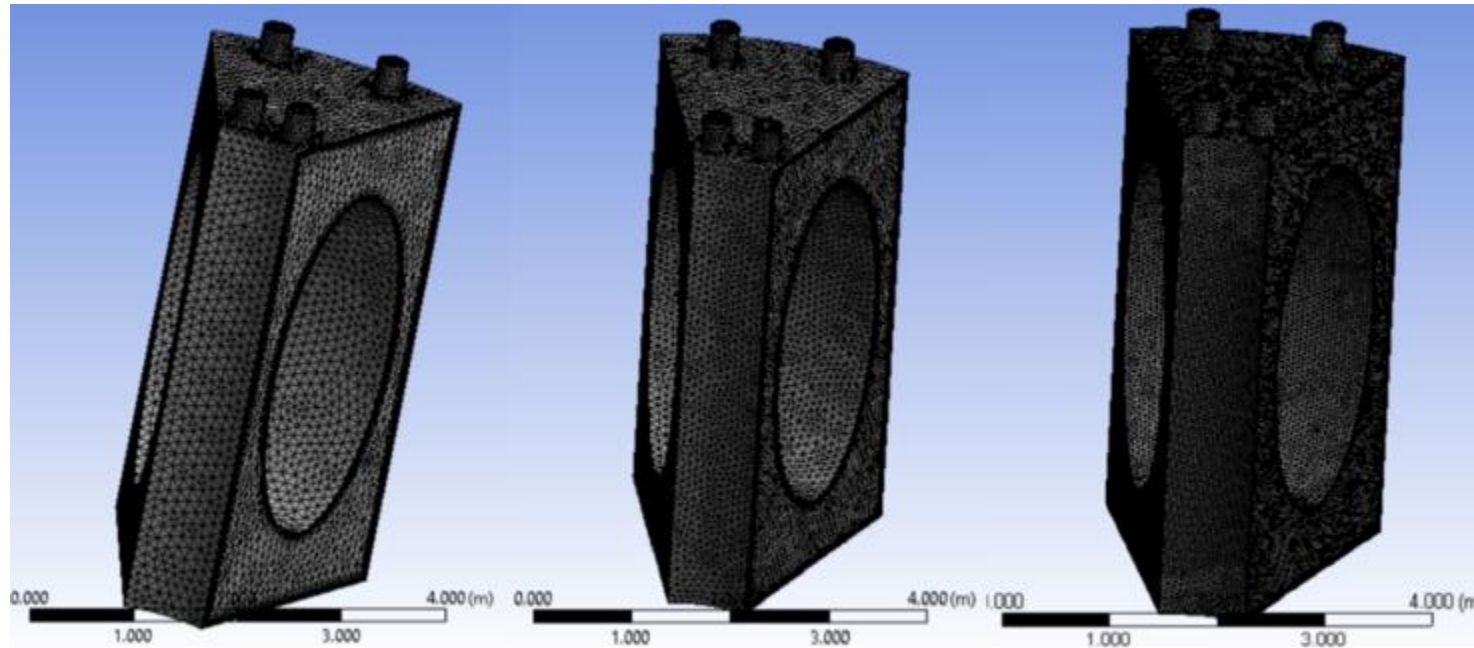


Figure 2.2: Mesh used in the FLiBe simulations from coarse to fine

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

- As shown in the figure, the solutions of three meshes are nearly identical, so **solutions are mesh independent**.

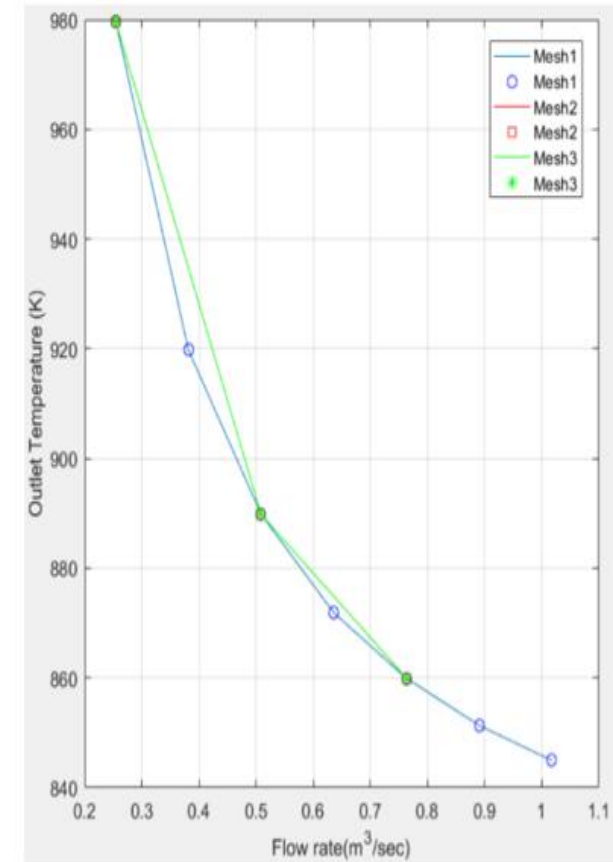


Figure 2.3: Outlet temperature dependence on flow rate comparing usage of three different meshes.

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

Both Standard k- ϵ and realizable k- ϵ are suitable for the simulations, and SST k- ω solution will not be considered due to its **bad convergence**.

TABLE 2.1: COMPARING BETWEEN SOLUTIONS OF THE THREE TURBULANCE MODELS

No.	Turbulence model	Outlet temperature(K)
1	Standard k- ϵ	871.8652
2	Realizable k- ϵ	871.8504
3	SST k- ω	862.0816

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

2. Solid blanket:

Points to be displayed	Strategy
The dependency of the solution on mesh element size	By using 2 meshes of 385749, and 541992 elements
Outlet temperature dependence on inlet flow.	by changing inlet flow rate and calculating the outlet temperature. Cases: 1. with <u>surface heating</u> of 0.4 MW/m^2 with no volumetric heating 2. with <u>surface heating</u> of 0.6 MW/m^2 and <u>volumetric heating</u> of 2 MW/m^3 .

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

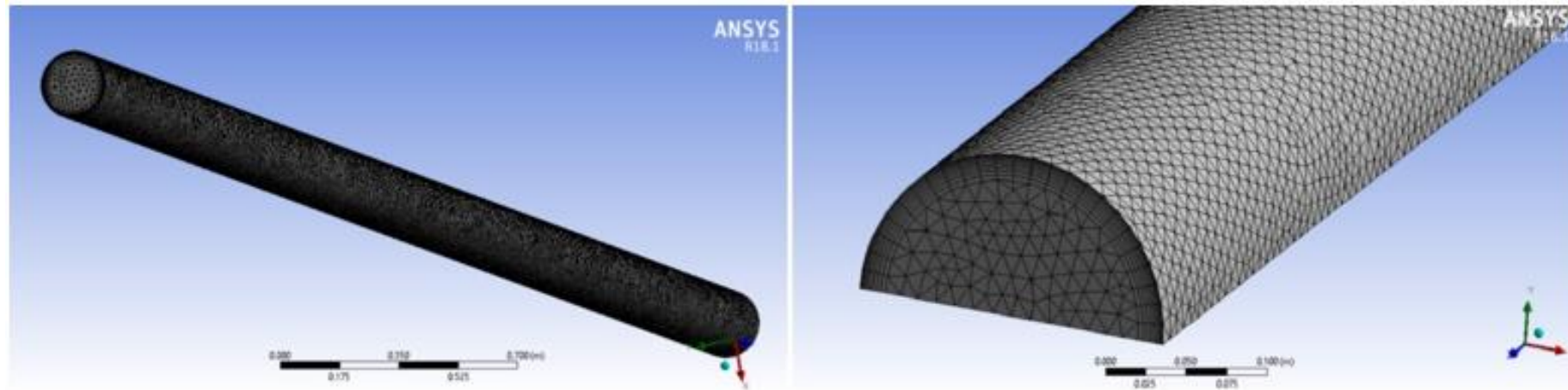


Figure 2.4: a) Helium pipe coarser mesh. b) Helium pipe finer mesh.

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

- In case of surface heating of 0.4 MW/m^2 without volumetric heating, it is clear from the Figure that the solution is **mesh independent**.

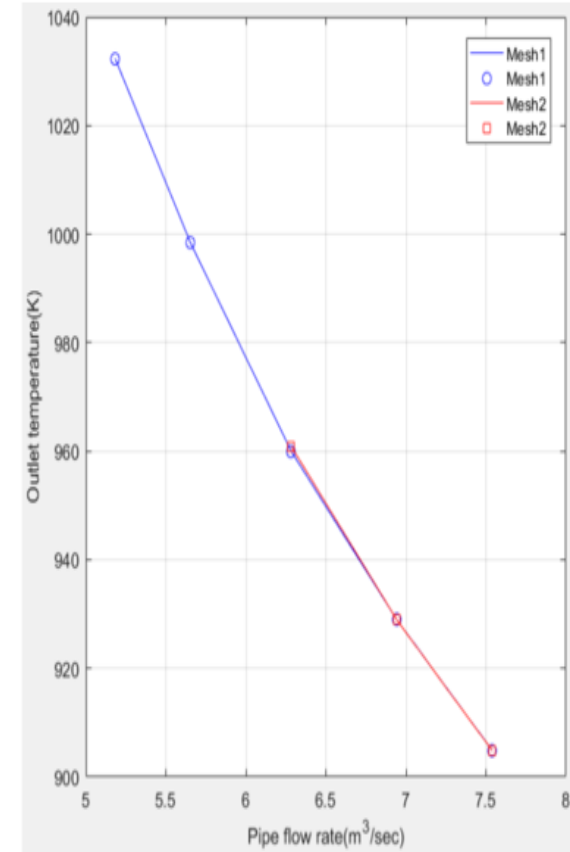


Figure 2.5: Outlet temperature dependence on flow rate, $q'' = 0.4 \text{ MW/m}^2$, assuming no volumetric heating

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Computational model:

- In case of surface heating of 0.6 MW/m^2 and volumetric heating of 2 MW/m^3 , it is clear from the Figure that **the three turbulence models** have different solutions with the coarser mesh and nearly identical solutions with the fine mesh, so **the coarser mesh will not be trustable**.

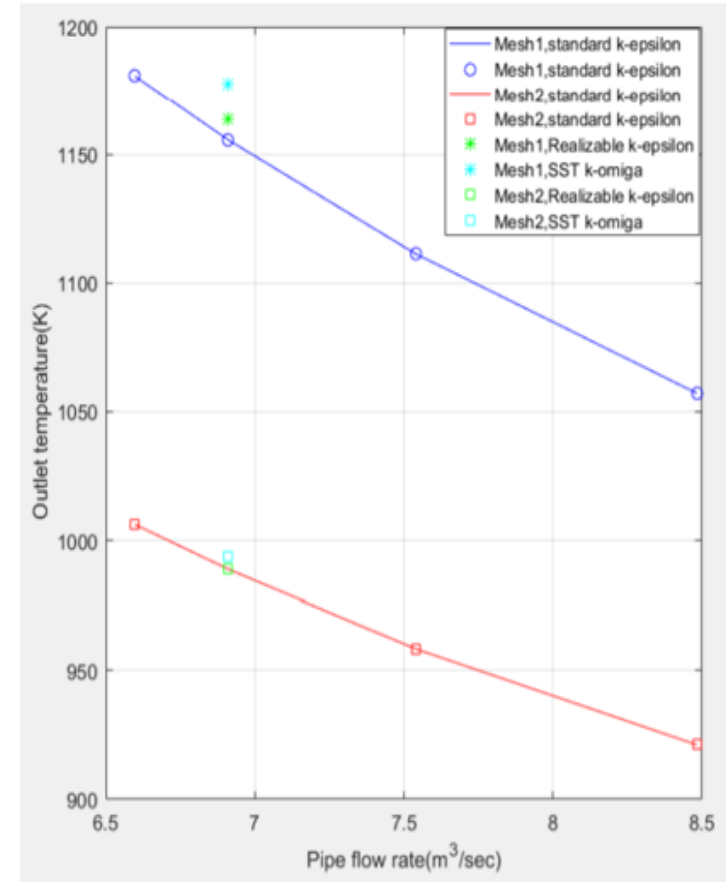


Figure 2.6: Outlet temperature dependence on flow rate, $q'' = 0.6 \text{ MW/m}^2$, $q''' = 2 \text{ MW/m}^3$.

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Results and discussion:

1. Immersion liquid blanket:

- Figure 2.3 shows that outlet temperature **decrease with increasing** inlet flow rate, and Inlet flow rate is necessary to exhaust heat and keep the outlet temperature in the range considered in ARC design which **decreases** pumping power.

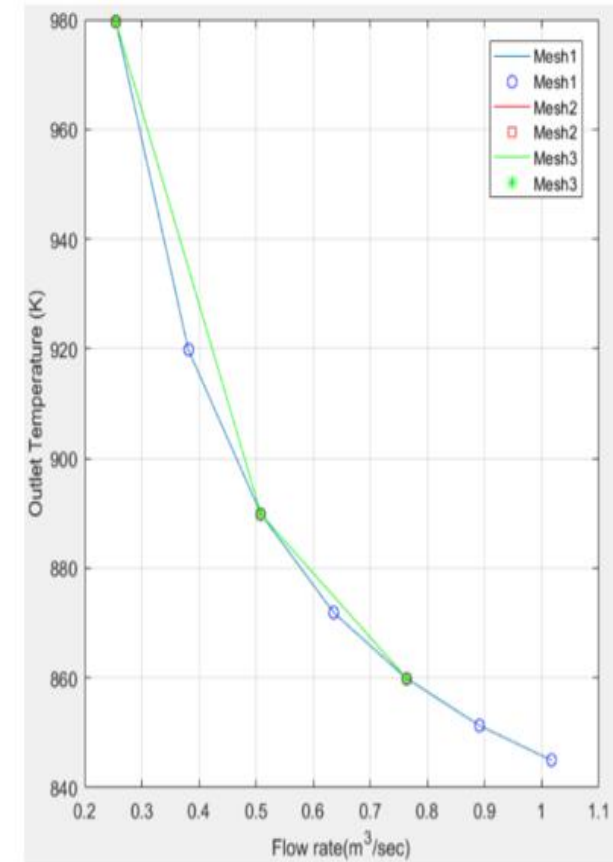


Figure 2.3: Outlet temperature dependence on flow rate comparing usage of three different meshes.

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Results and discussion:

2. Solid blanket:

- For one pipe when assuming heat flux = 0.4 MW/m^2 with no volumetric heating and inlet temperature of 623 K (like condition in ARIES.I), the heat exhausted is found to be 1.657 MW for one pipe, so 131 pipes are needed to exhaust 216.873 MW with average total flow rate of $982.5 \text{ m}^3/\text{sec}$ and **199 pipes are needed to exhaust 329.4 MW** with total flow rate of $1492.5 \text{ m}^3/\text{sec}$.
- For one pipe when assuming heat flux = 0.6 MW/m^2 , volumetric heating of 2 MW/m^3 , and inlet temperature 623 K , the heat exhausted is found to be 2.89 MW for pipe, so 75 pipe will be necessary to exhaust 216.873 MW with total flow rate of $562.5 \text{ m}^3/\text{sec}$ and **114 to exhaust 329.4 MW** with total flow rate of $855 \text{ m}^3/\text{sec}$.

2. Comparison between liquid blanket and solid blanket from heat transfer point of view.

Conclusion:

- At keeping outlet temperature & pressure drop within the design range for both ARC and ARIES, the following was found:
 1. **Helium gas** should be pumped with a **much higher flow rate** which means **more pumping power**.
 2. Pressure drop in **Helium** is much **larger** than in **FLiBe**.
 3. **FLiBe** has **more ability to exhaust heat** due to its high volumetric heat capacity.
 4. When using solid blanket, **increasing thermal efficiency** is achievable by increasing the outlet temp. of **Helium**, but this needs very high pressure which **raises safety concerns**.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

What is MHD?

- The fundamental concept behind MHD is that **magnetic fields can induce currents in a moving conductive fluid**, which in turn **creates forces on the fluid** and also changes the magnetic field itself.
- The study of mentioned MHD is concerned with the **molten salt** (blanket) not the plasma. The liquid metal is used as the coolant and as the tritium breeding material.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

What is MHD?

Dimensionless groups:

- In a given geometry, we can characterize MHD flows by mainly three dimensionless groups:
 1. Magnetic Reynolds number (R_m)
 1. Hartmann number (Ha)

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

What is MHD?

1. Magnetic Reynolds number (R_m)

- Ratio between inductive and diffusive terms in the magnetic induction equation.
- This number is analogous to the Reynolds number of ordinary fluid mechanics, which is used to determine whether or not a fluid flow will smooth out or become turbulent.

$$R_m = \mu_0 \sigma V L$$

μ_0 : magnetic permeability of free space

σ : the electrical conductivity

V : fluid velocity

L : length characteristic of the fluid

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

What is MHD?

2. Hartmann number (Ha)

- The ratio of electromagnetic force to the viscous force.
- A dimensionless number which gives a measure of the relative importance of drag forces resulting from magnetic induction and viscous forces.

$$Ha = B_o L \sqrt{\frac{\sigma}{\mu}}$$

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

What is MHD?

Governing equations:

$$\nabla \cdot \bar{u} = 0$$

$$\rho \frac{\partial \bar{u}}{\partial t} + \rho (\bar{u} \cdot \nabla) \bar{u} = -\nabla p + \mu \nabla^2 \bar{u} + \bar{J} \times \bar{B}_0$$

$$\nabla \cdot \bar{J} = 0$$

$$\bar{J} = \sigma (-\nabla \phi + \bar{u} \times \bar{B}_0)$$

$$0 = \nabla^2 T + Q$$

$$\nabla \cdot \bar{u} = 0$$

$$0 = -\nabla p + \frac{1}{Ha} \nabla^2 \bar{u} + \bar{J} \times \hat{y} + T \hat{x}$$

$$\nabla \cdot \bar{J} = 0$$

$$\bar{J} = -\nabla \phi + \bar{u} \times \hat{y}$$

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

What is MHD?

The flow features are influenced by the relative conductivity between the duct wall and the fluid.

- **Shercliff's case** is when all the walls are non-conducting.
- **Hunt case** is when walls are conducting.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Validation of Fluent-MHD model with FLiBe

- The pursuit of this part is **validating Hunt case for FLiBe** and then **simulate Shercliff case**. The results of Hunt case would be reproduced as done by M. J. Bluck and M. J. Wolfendale.
- The used dimensions in this model are $40 \times 40 \times 400$ mm. The used structured mesh in this model is 471000 elements and 10 layers in the boundary layer as in Figure 3.4. The properties of FLiBe used in the model are mentioned in Table 3.2.
- Two thermal conducting walls perpendicular on y-direction the below wall at 820 K and the above wall is at 780 K, other walls are thermally insulating walls.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Validation of Fluent-MHD model with FLiBe

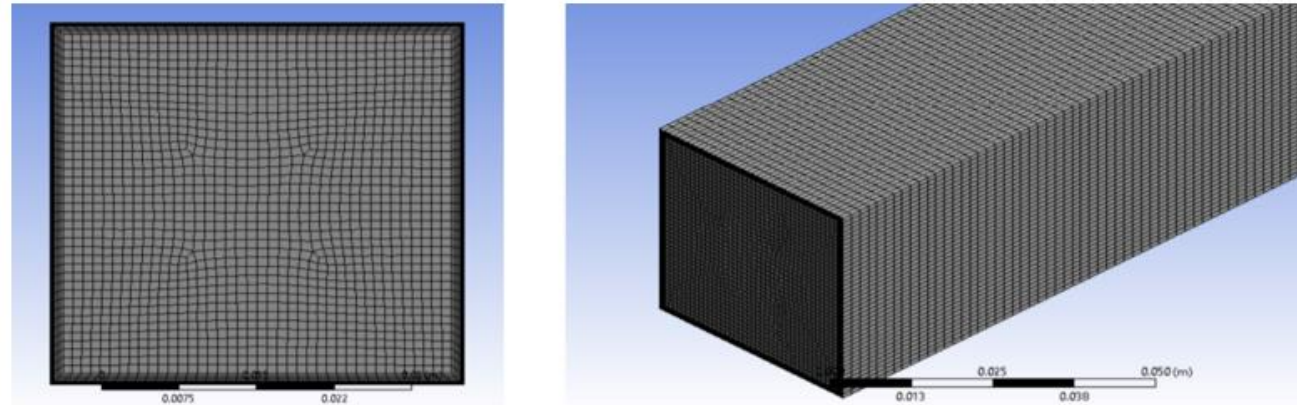


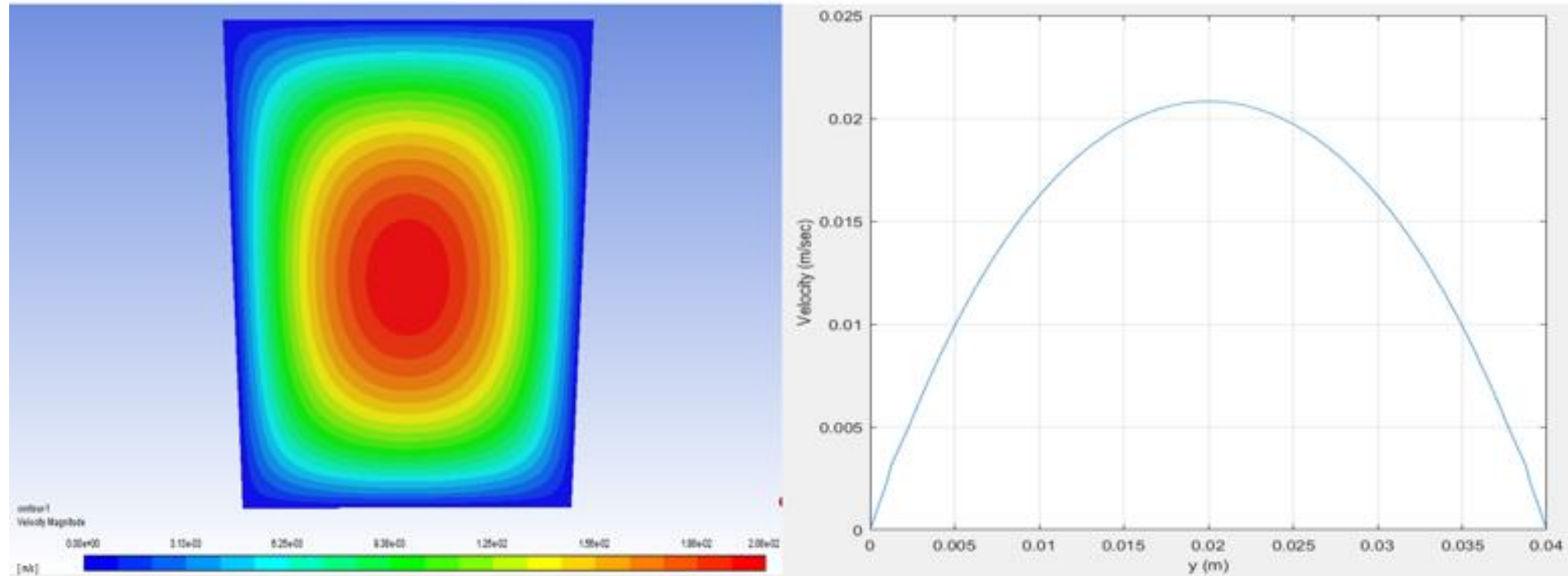
Figure 3.4: a) Front view of mesh structure. b) Isometric view of mesh structure

Table 3.2: Fluid properties

Property	Typical value
Density (kg/m ³)	2120
Dynamic viscosity (Pa.s)	0.0116
Electrical conductivity (S/m)	115
Wall conductivity (S/m)	9.22×10^6

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Validation of Fluent-MHD model with FLiBe



No magnetic field

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Validation of Fluent-MHD model with FLiBe

The comparison between Bluck model and our results in Figures 3.5, 3.6, and 3.7 shows that Fluent-MHD could successfully simulate Hunt case for FLiBe.

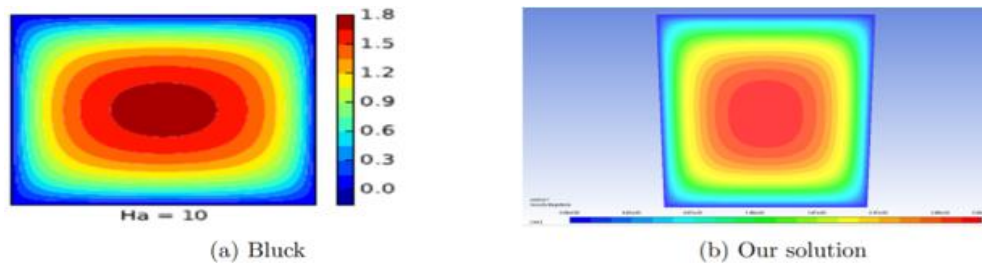


Figure 3.5: Comparison between Bluck results and our results at $Ha = 10$.

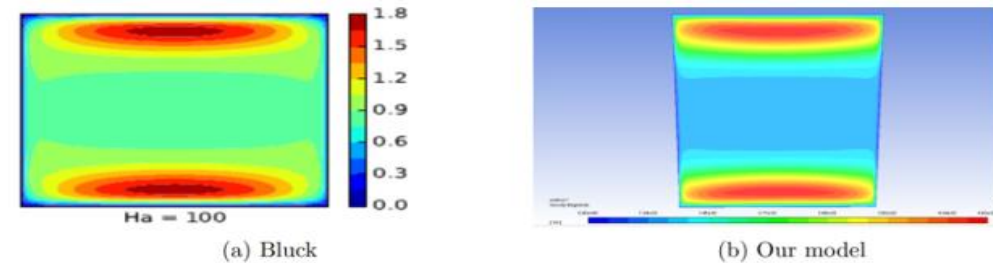


Figure 3.6: Comparison between Bluck results and our results at $Ha = 100$.

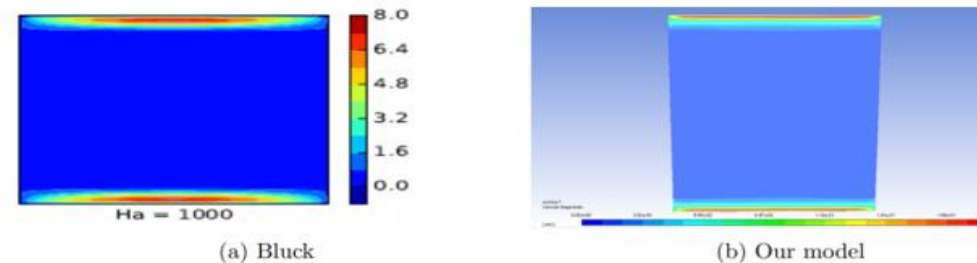


Figure 3.7: Comparison between Bluck results and our results at $Ha = 1000$.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Validation of Fluent-MHD model with FLiBe

Our results were extended to Shercliff case at different Hartmann numbers as in Figure 3.8 and comparing them with Hunt case at the same Hartmann numbers.

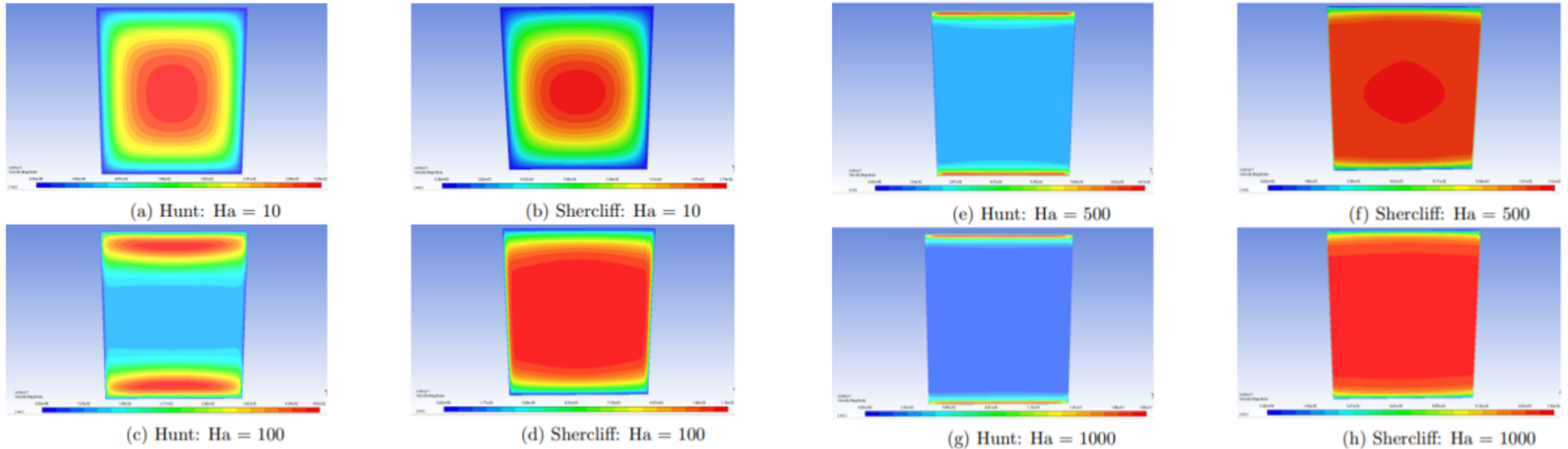


Figure 3.8: Comparison between Hunt and Shercliff cases for different Hartmann numbers

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

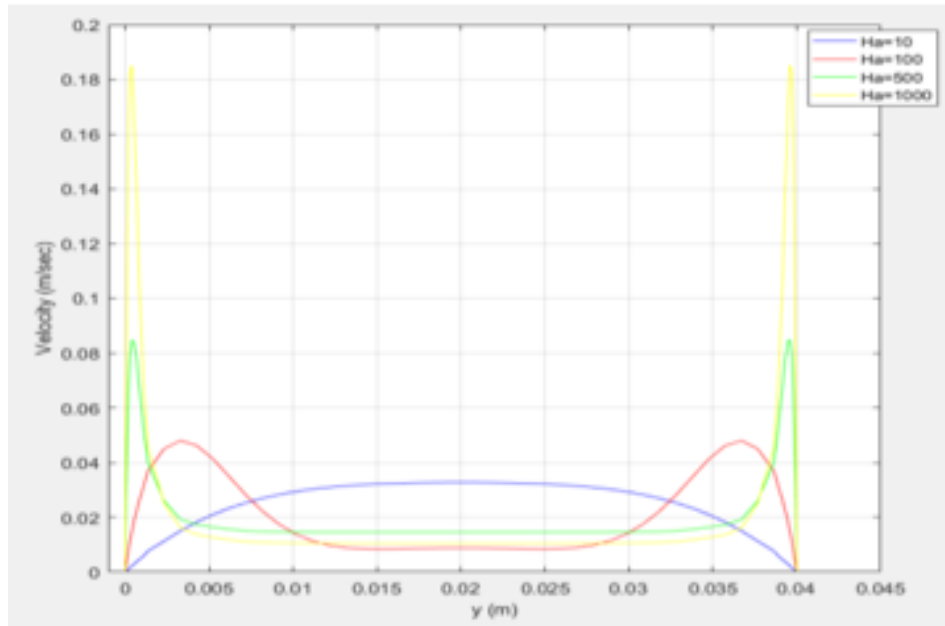
Validation of Fluent-MHD model with FLiBe

Figure 3.9 shows that:

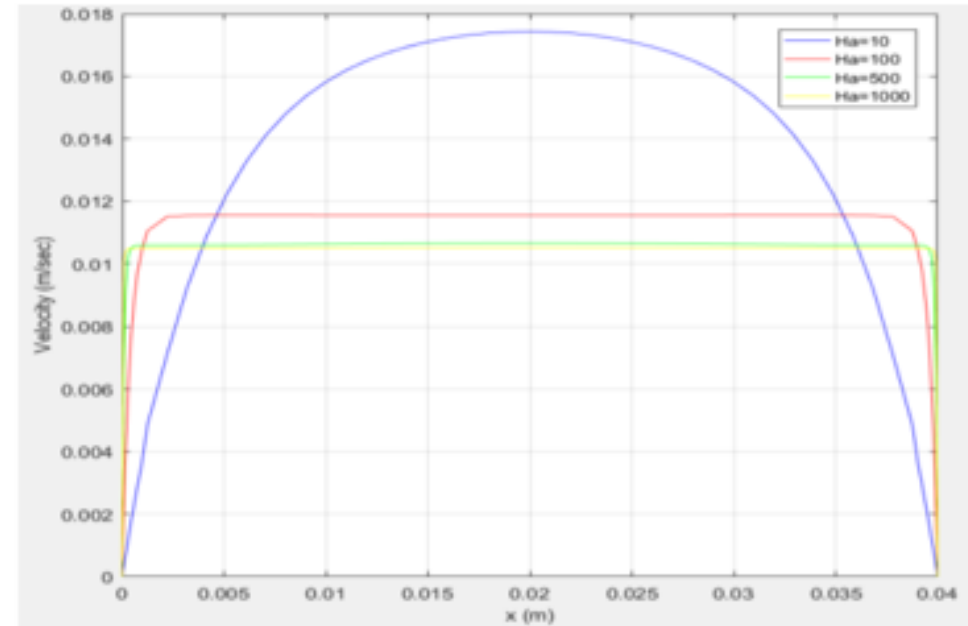
- The jets increase with increasing Hartmann number.
- The velocity distribution in Shercliff case through Hartmann numbers tends to deviate from normal shape to box-like shape.
- Since Fluent-MHD module is validated for FLiBe for both Hunt and Shercliff cases it could be used for simulating effects of MHD on flow.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Validation of Fluent-MHD model with FLiBe



(a) Hunt case



(b) Shercliff: Hartmann layers

Figure 3.9: Velocity distribution at the outlet at different Hartmann numbers

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Magnetoconvection

- The pursuit of this part is studying the effect of magnetic field on the natural convection which is known as magnetoconvection phenomenon.
- The geometry used in this study is 40×40×300 mm.
- The mesh used for this model consists of 758400 elements and 18 layers as in the boundary layers to capture the physics of convection.
- The **properties of FLiBe** used in this part are temperature-dependent properties.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Magnetoconvection

The model is built as follows:

- Two thermal conducting walls perpendicular on y-direction the **below wall at 820 K** and the **above wall is at 780 K**.
- Other walls are **thermally insulating** walls.
- The inlet **temperature profile is a linear function** determined by the boundary conditions of walls temperatures.
- All walls are **electrically insulated**.
- The gravitational acceleration is defined in the flow direction.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Magnetoconvection

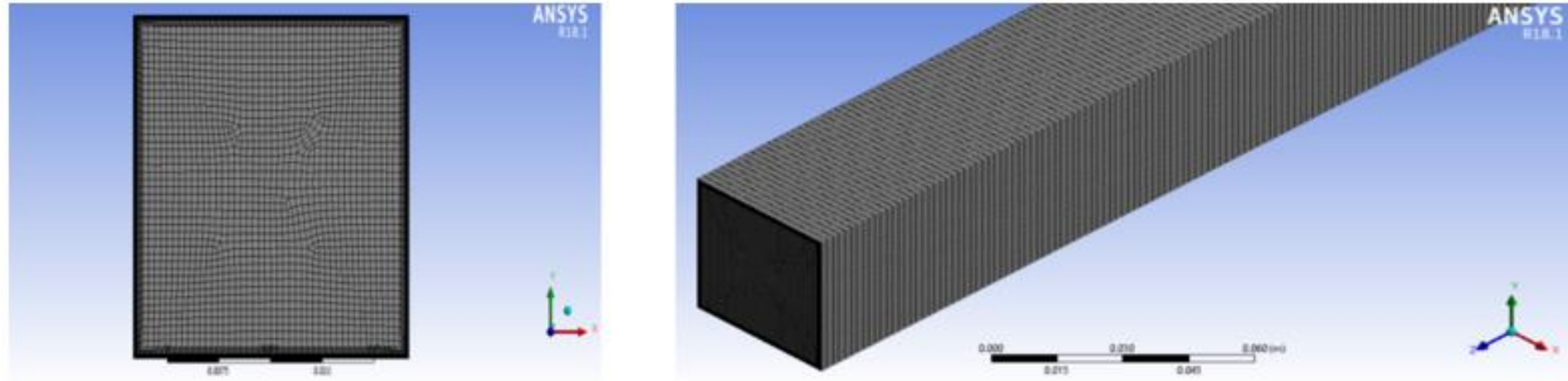


Figure 3.11: a) Front view of mesh structure. b) Isometric view of mesh structure

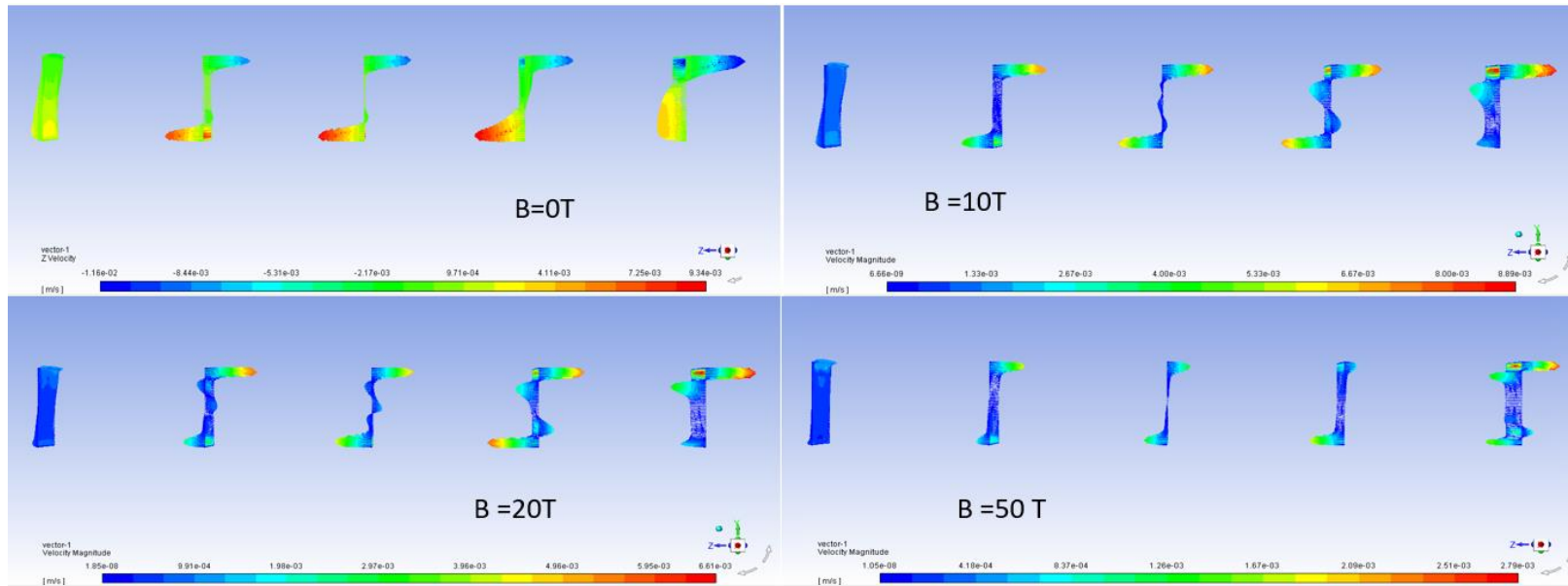
3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Magnetoconvection

- **Increasing the magnetic field** suppresses the flow and decrease the velocity especially near the walls which **decreases heat transfer** due to natural convection in favor of thermal conduction.
- Our concentrate must be more on **magnetic field range ~ 10 T** as the conditions in ARC.
- Effects of MHD on natural convection cannot be ignored in ARC design.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Magnetoconvection



Velocity distribution through the duct

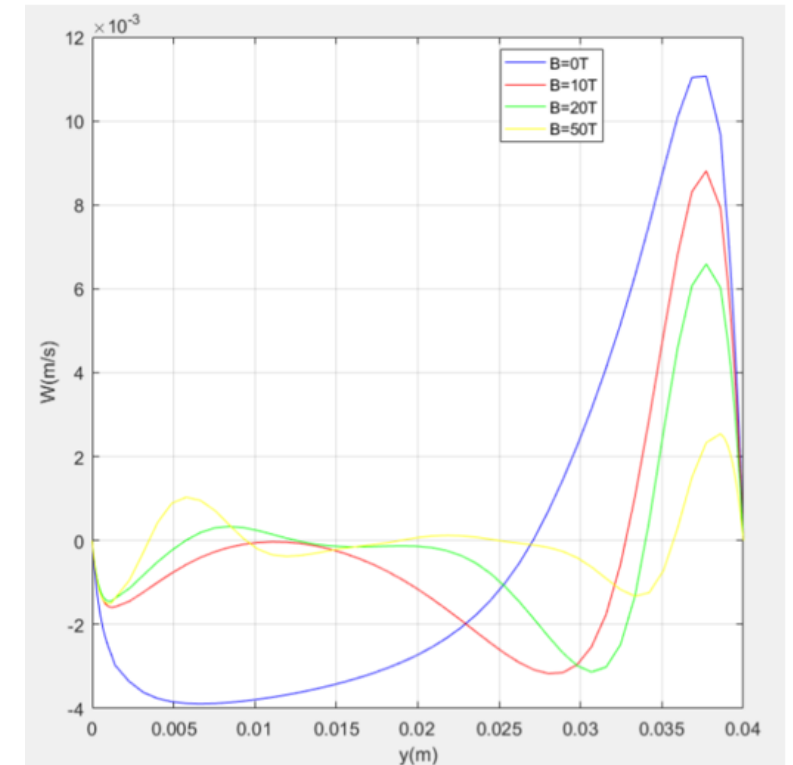
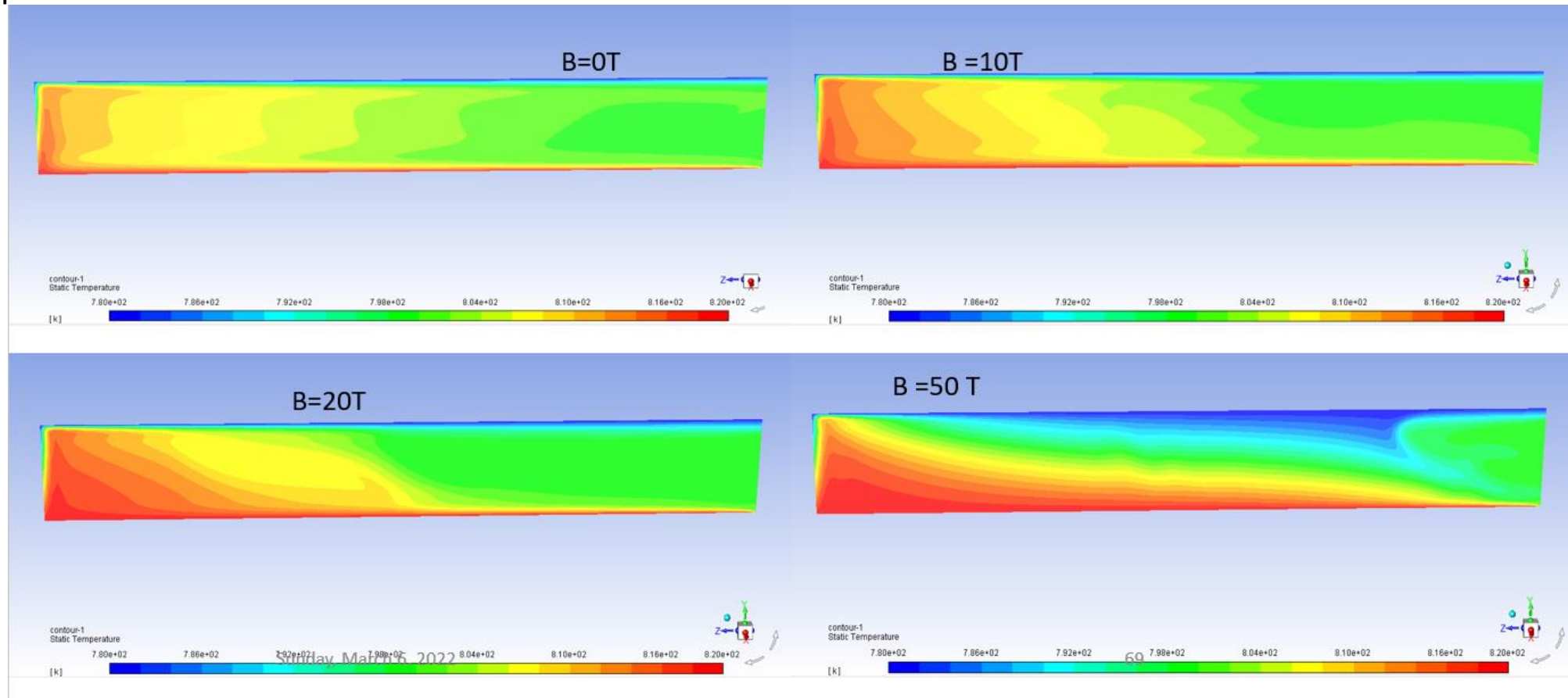


Figure 3.13: velocity distributions at the outlet

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Magnetoconvection

Temperature distribution:



3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

MHD effect on turbulence and pressure drop through a circular pipe

- In this part, the study will be moved from the effects of MHD on laminar flow regimes to a more realistic case which is the effect on the turbulence in a circular pipes.
- Three turbulence models will be compared (standard $k-\varepsilon$, realizable $k-\varepsilon$, and $k-\omega$ SST) to find which one is more stable to be used.
- The used geometry in this model is a cylinder with radius 10 mm and length 800 mm.
- Half cylinder.
- The used two meshes have 463600, and 713200 elements with 6 and 8 layers in the boundary layer respectively.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

MHD effect on turbulence and pressure drop through a circular pipe

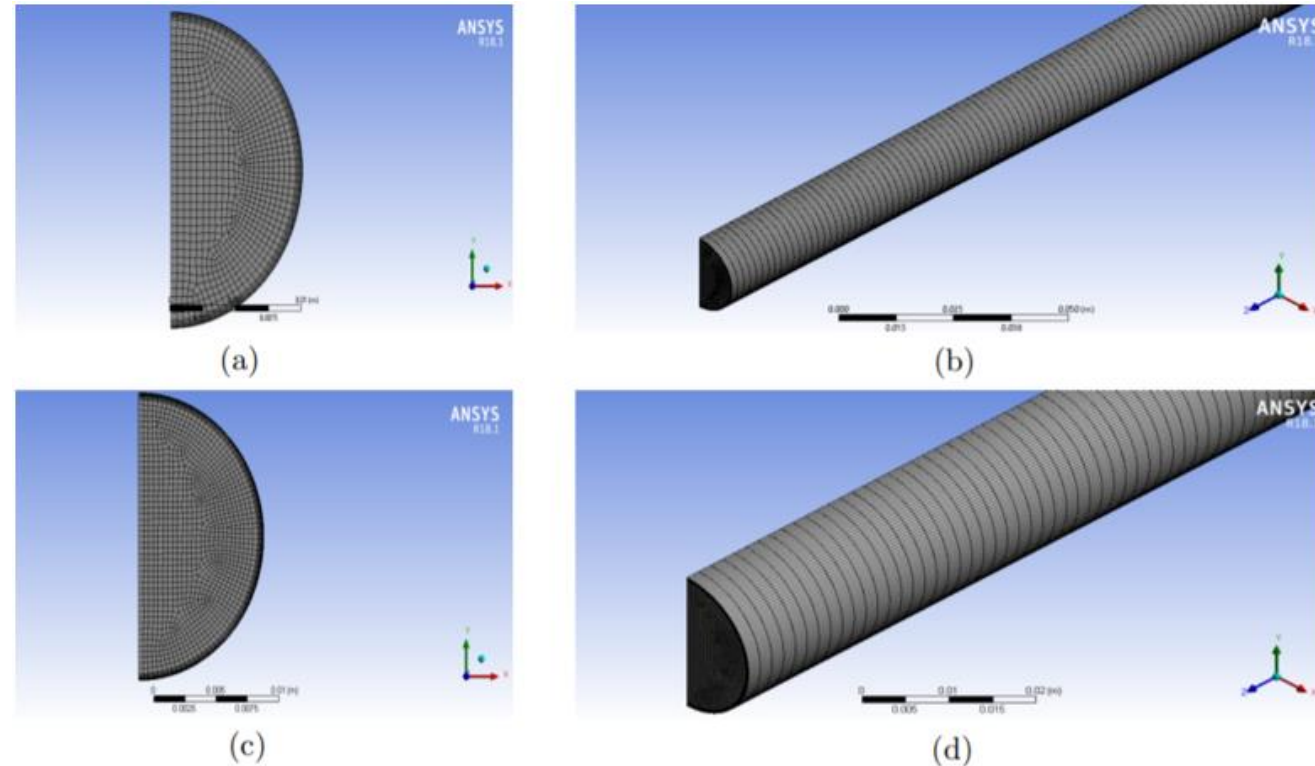
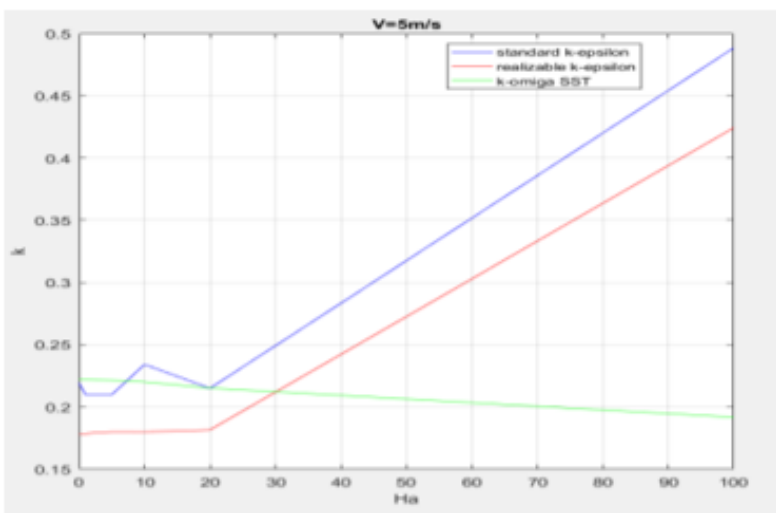


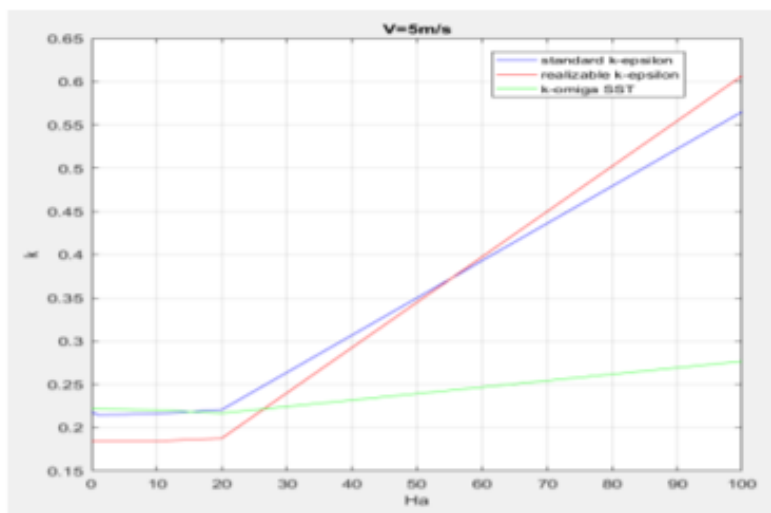
Figure 3.12: (a) Coarse mesh front view. (b) Coarse mesh isometric view.
(c) Fine mesh front view. (d) Fine mesh isometric view.

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

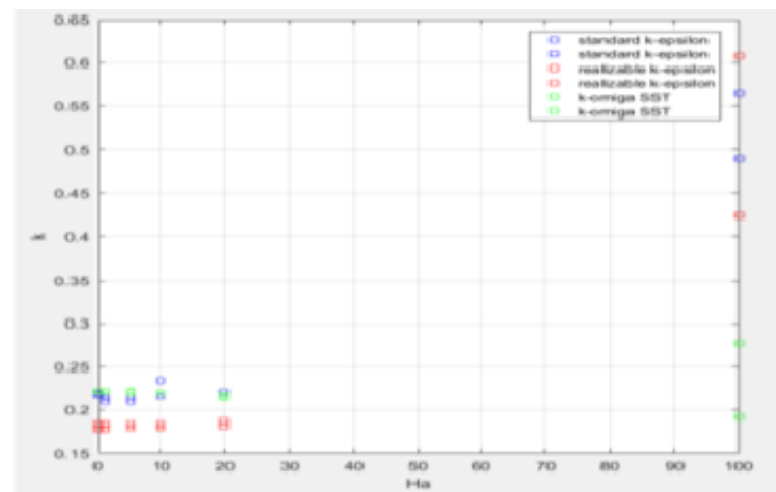
MHD effect on turbulence and pressure drop through a circular pipe



(a) Coarse mesh



(b) Fine mesh



Comparison between two meshes solutions for the three models together

Figure 3.13: Comparison of effect of mesh on solution of the effect of MHD on turbulent kinetic energy at the outlet the pipe

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

MHD effect on turbulence and pressure drop through a circular pipe

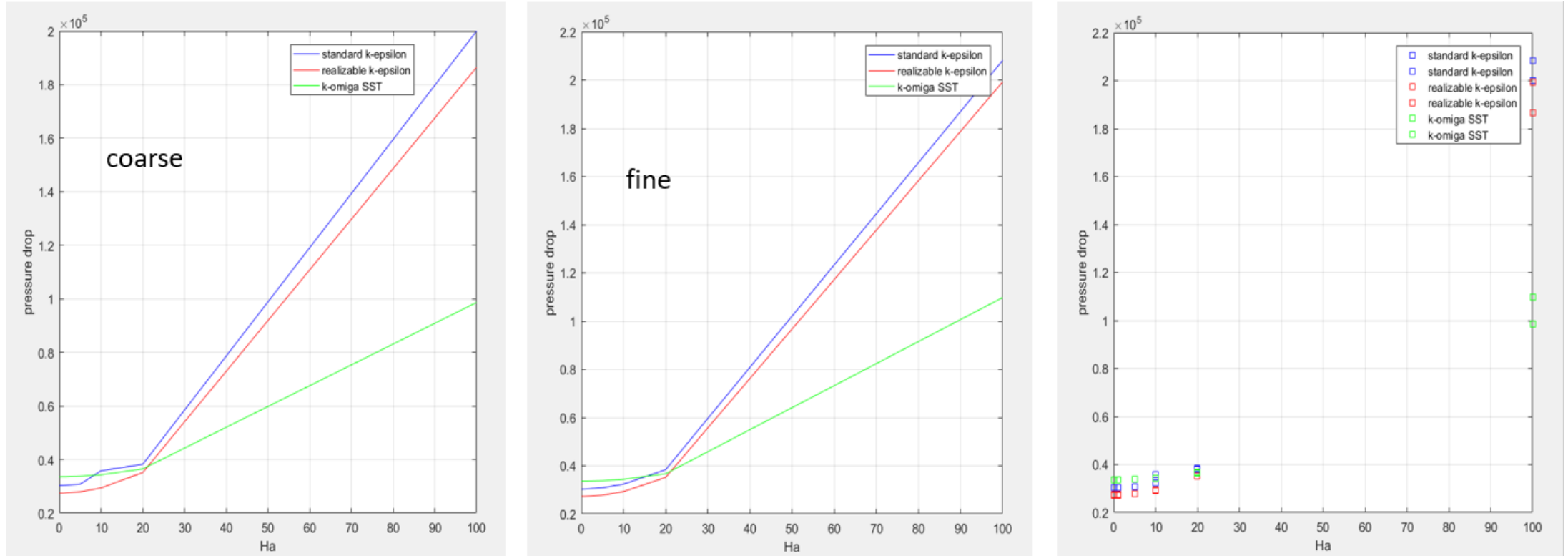
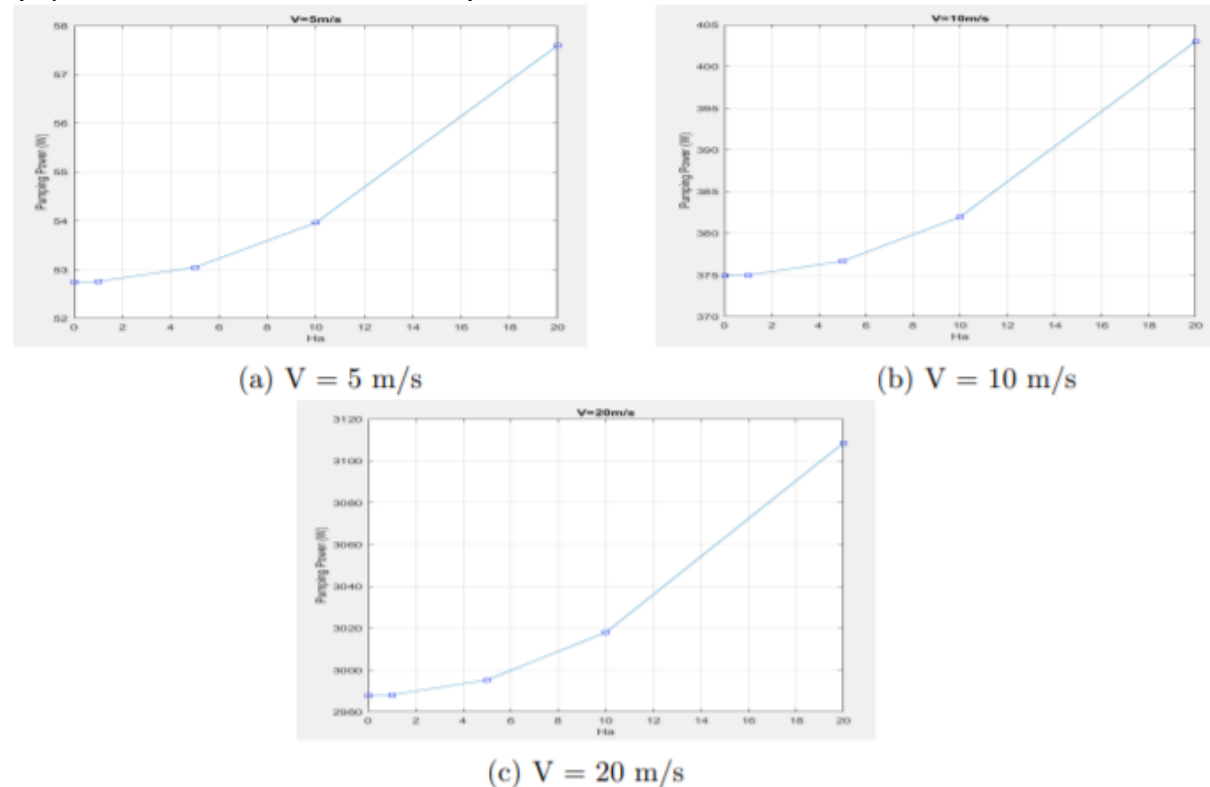


Figure 3.15: Effect of MHD on pressure drop using the three models and two meshes

3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

MHD effect on turbulence and pressure drop through a circular pipe

- Figure 3.16 shows that we conclude that the existence of magnetic field increases the pumping power approximately 4.8 W for $v=5\text{m/s}$, 28 W for 10m/s , and 1022 W for $v=20\text{m/s}$ when Ha increases from 0 to 20.



3. EFFECTS OF MAGNETOHYDRODYNAMICS ON FLiBe

Conclusion

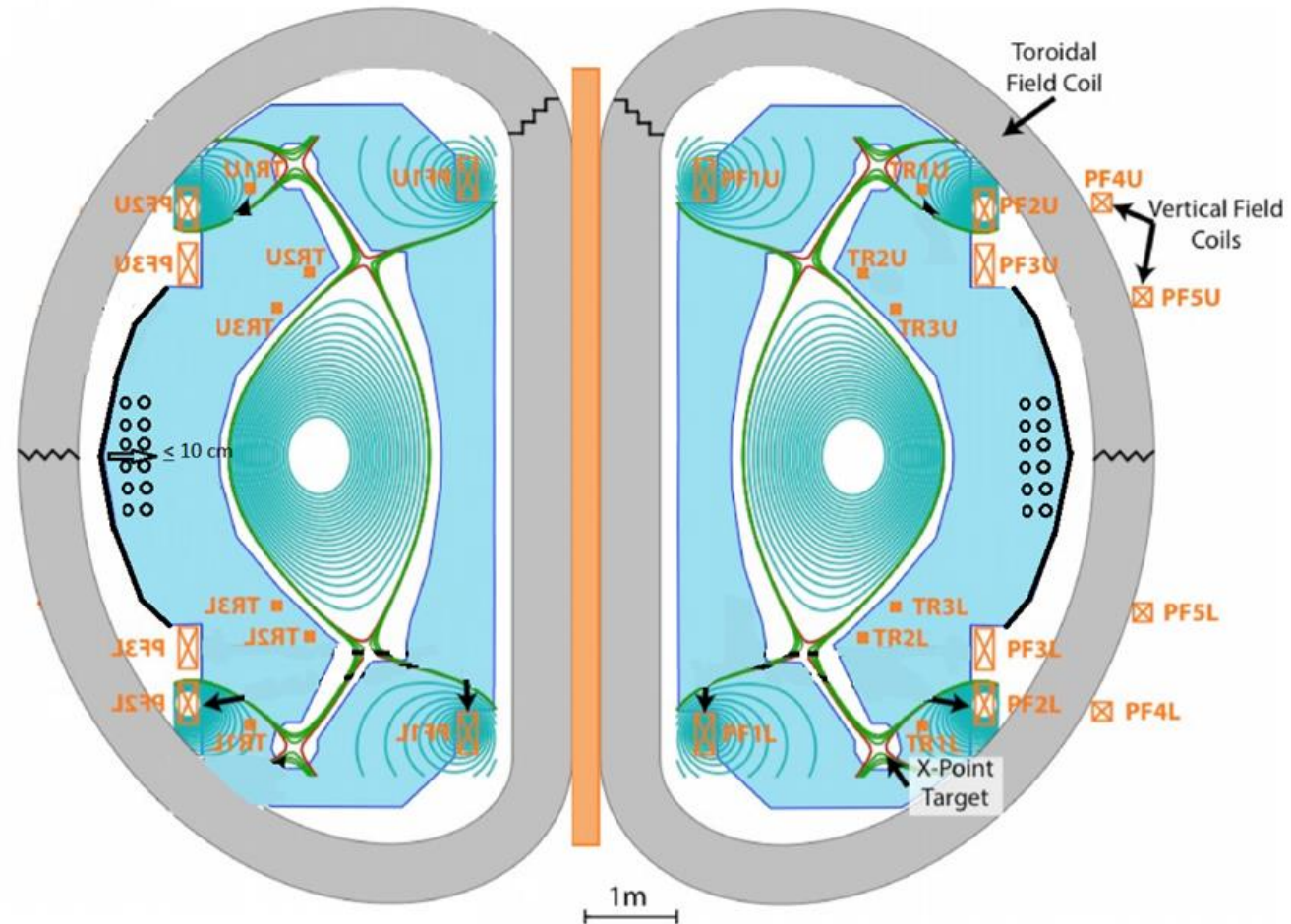
It was concluded that:

- The turbulence is suppressed by increasing Hartmann number.
- The pressure drop increases by increasing Hartmann number which increases required pumping power.
- So, Increasing the magnetic field suppresses the heat transfer rate and the effect of MHD cannot be ignored in ARC design.

4. Heat Exchanger For ARC Blanket.

- **The purpose:** design a heat exchanger for ARC blanket to transfer thermal power= 241.5 Mw.
- **Conditions and used material.** It was designed to be inside the FLiBe liquid blanket but at 10 cm apart from blanket surface. Inconel718 was used as a material for the pipes, and Helium gas as a fluid inside the pipes.
- **The type of the heat exchanger:** is cross-flow, which is better than counter-flow, because the number and the dimensions of the pipes at counter-flow required to transfer 241.5 Mw make the heat exchanger size larger than the permissible space, although counter-flow has better efficiency than cross.

4. Heat Exchanger For ARC Blanket.



4. Heat Exchanger For ARC Blanket.

FLiBe Parameters:

- The FLiBe parameters were made equal to the average the FLiBe parameters at three horizontal planes at **the middle and, above and below 0.5 m** from the middle of the tokamak.
- The parameters of FLiBe fluid are shown in the following figures 4.1, 4.2, and 4.3 :

4. Heat Exchanger For ARC Blanket.

FLiBe Parameters:

- The average temperature = 850 K.

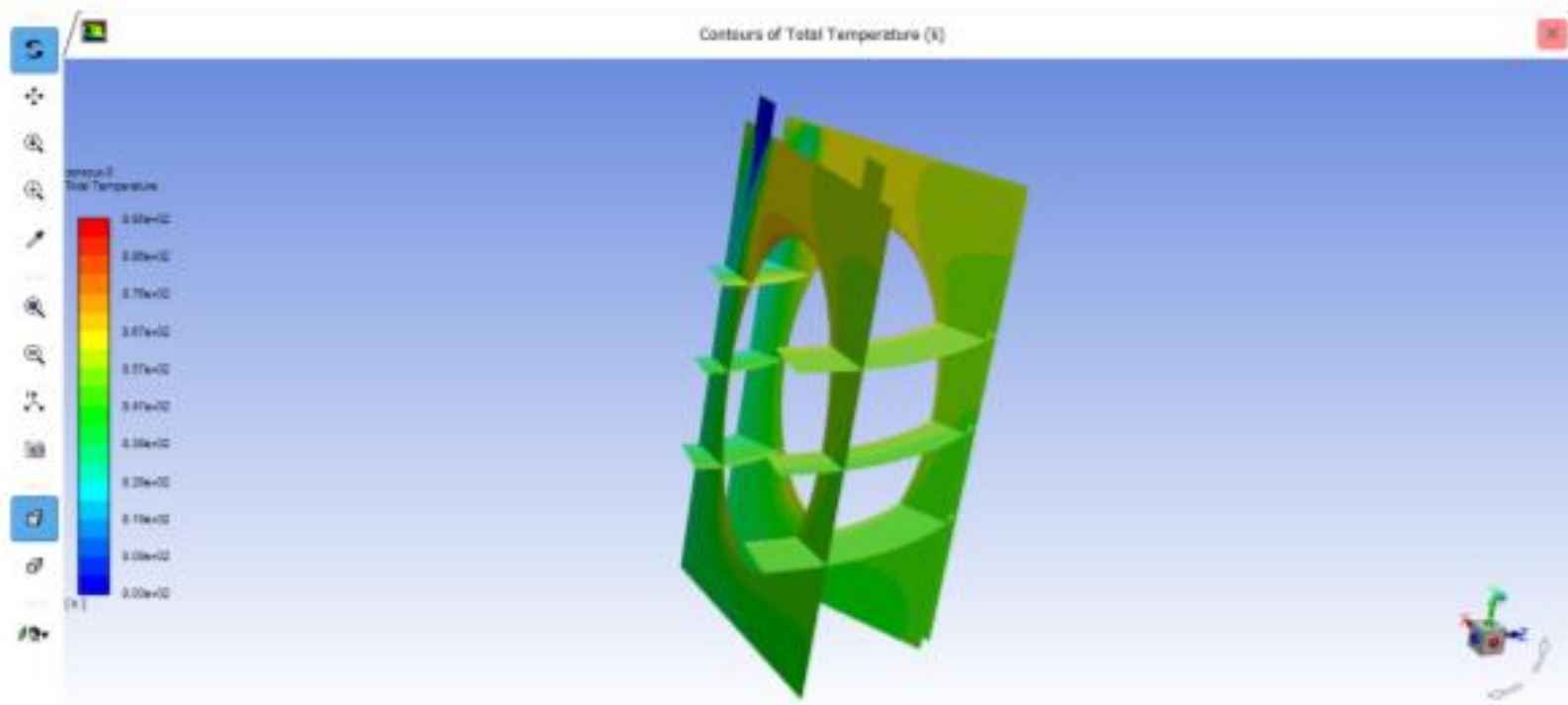


Figure 4.1: Static temperature of FLiBe fluid

4. Heat Exchanger For ARC Blanket.

FLiBe Parameters:

- The average velocity = 0.325 m/s, or 0.259 m/s.

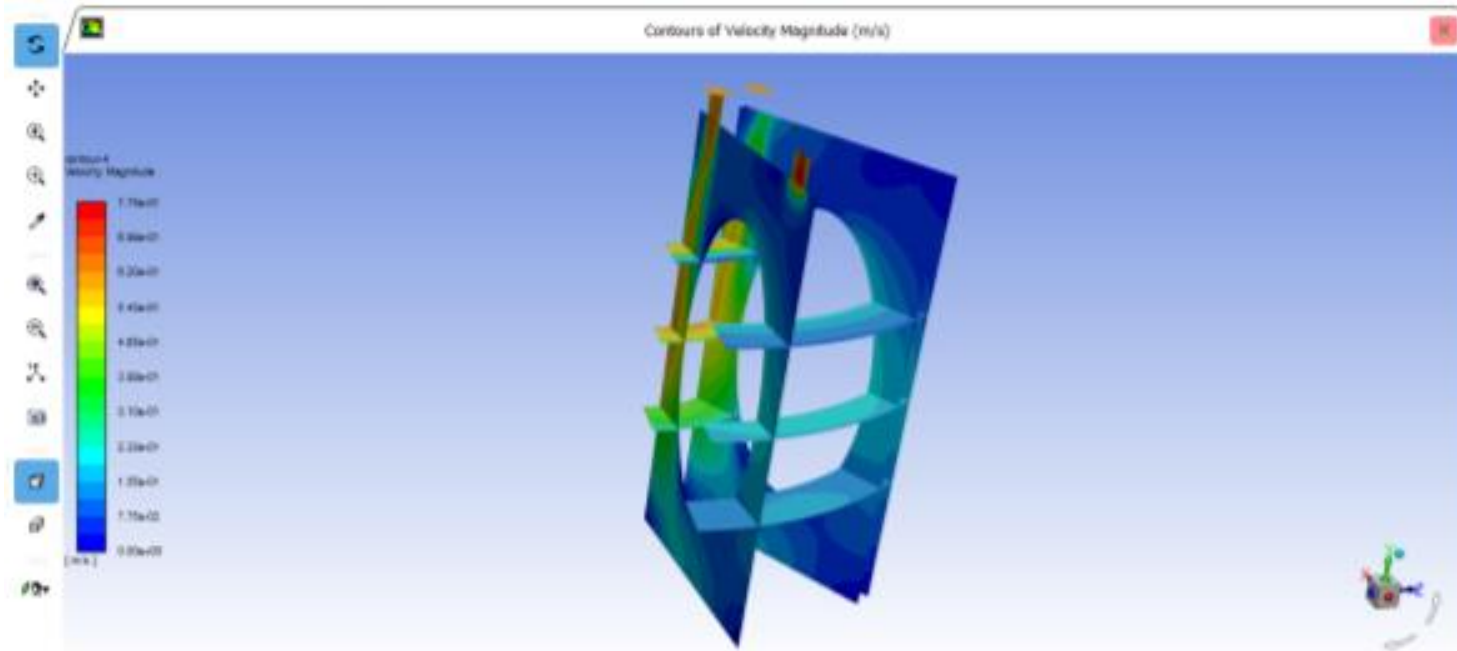


Figure 4.2: Velocity magnitude of FLiBe fluid

4. Heat Exchanger For ARC Blanket.

FLiBe Parameters:

- The average pressure = 700 pascal.

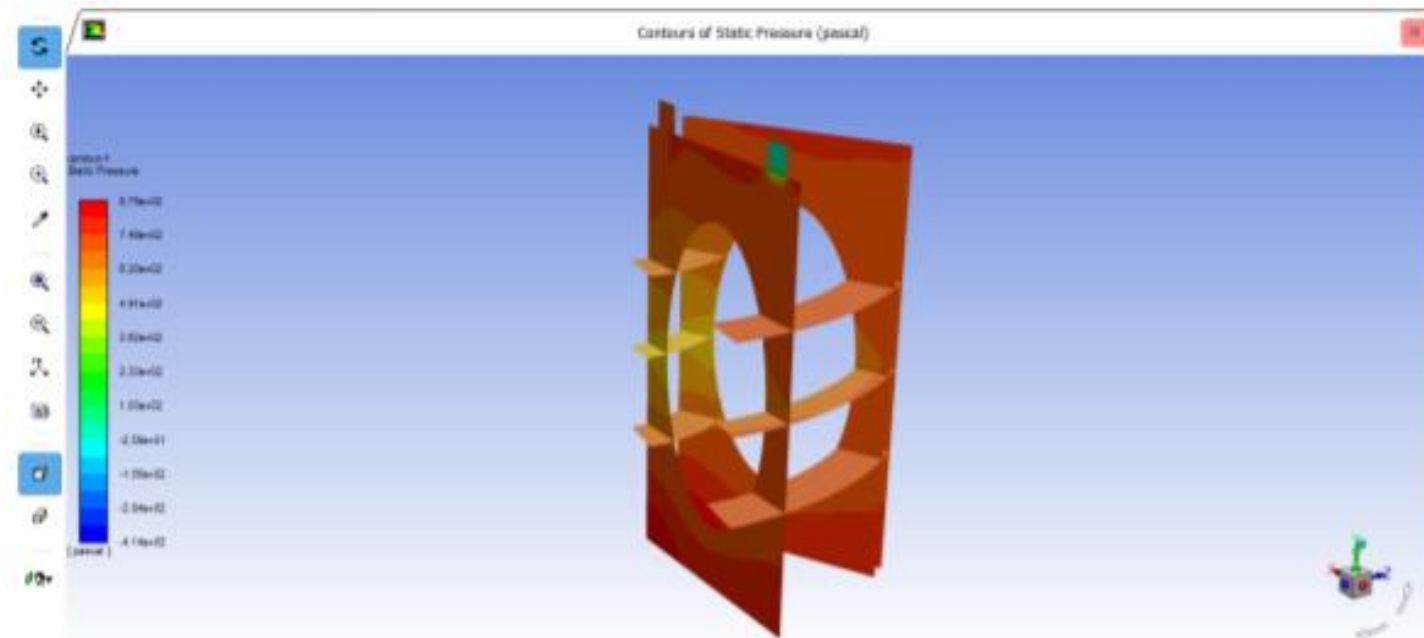


Figure 4.3: Static pressure of FLiBe fluid

4. Heat Exchanger For ARC Blanket.

Model description:

- The overall heat transfer coefficient and dimensions of the pipes were assumed to Calculate the number of the pipes.
- By using Eq. 35, The calculated overall heat transfer coefficient was computed. Then, Compared with the assumed.
- It was found that the permissible dimensions and pipes' number will be achieved when Helium inlet temperature is at 500K.

4. Heat Exchanger For ARC Blanket.

Model description:

- A lot of different pipes' dimensions was tried to find the dimensions, at which the assumed over all heat transfer coefficient equal to the calculated and have the appropriate number of pipes to be placed at the limited space to transfer 241.5MW (width = 10 cm apart from blanket surface, the outer diameter of the vacuum vessel is 31.41m, and the allowed height is 2.5m).
- Different dimensions were tried. Then, calculating the associated number of the pipes, and comparing the size of the heat exchanger with the allowed size, and preferring between these different designs.

4. Heat Exchanger For ARC Blanket.

Model description: (Used data):

- FLiBe inlet temperature ($T_{h,in}$) = 850 K.
- FLiBe outlet temperature ($T_{h,out}$) = 830 K.
- FLiBe inlet pressure ($P_{h,in}$) = 700 pascal.
- FLiBe inlet velocity ($v_{h,in}$) = 0.325 m/s or 0.259 m/s.
- FLiBe density (ρ_{FLiBe}) = 1940 Kg/m³.
- FLiBe Thermal conductivity (K_{FLiBe}) = 1.1 w/m.K .
- FLiBe dynamic viscosity (μ_{FLiBe}) = 0.006 Pa.s .
- Helium inlet temperature ($T_{c,in}$) = 500 K.
- Helium outlet temperature ($T_{c,out}$) = 840K.
- Helium inlet pressure ($P_{c,in}$) = 6 M pascal.
- Helium density (ρ_{He}) = 4.5709 Kg/m³.
- Helium thermal conductivity (K_{He}) = 0.2613 w/m.K .
- Helium dynamic viscosity (μ_{He}) = 3.3217×10^{-5} Pa.s .
- Helium specific heat capacity at constant pressure (Cp_{He}) = 5195J/Kg.K .
- Inconel718 density ($\rho_{Inconel718}$) = 819 Kg/m³.
- Inconel718 thermal conductivity ($K_{Inconel718}$) = 22.49 w/m.K .
- Inconel718 yield stress at 900 K = 800 Mpa.

4. Heat Exchanger For ARC Blanket.

Initial values of the dimensions and number of the pipes:

- Because the range of the dimensions of the pipes and Helium pressure **wasn't specified**, the designed data of several heat exchangers of different nuclear power plants generate different powers **was collected** at table 4.1. Then, **Taking the average values at 241.5MW.**

4. Heat Exchanger For ARC Blanket.

Initial values of the dimensions and number of the pipes:

- Because the range of the dimensions of the pipes and Helium pressure **wasn't specified**, the designed data of several heat exchangers of different nuclear power plants generate different powers **was collected** at table 4.1. Then, **Taking the average values at 241.5MW.**

4. Heat Exchanger For ARC Blanket.

Initial values of the dimensions and number of the pipes:

Table 4.1: The dimensions of the pipes and the Helium pressure as the fluid inside the pipes for different nuclear power plants generate different powers.

	Power	D_{out}	D_{in}	P_{in}	length
1	1000			6.3	20.7
2	125	1.75	1.32	5.8	8.5
3	840			14.7	
4	352			16.5	
5	170			5.15	14.2
6	110.5	1.4	1	5.4	5.38
7	76.9	2.1	1.6	5.2	10.9
8	105.5			6.92	
9	302.5	3	2.2	7.46	49
10	454			7.46	48.4
11	355	2.54	2.04	7.23	35
12	65				
13	10	2.69	2.14	4.2	
14	168			5.15	14
15	10.1	2	1.6	4.35	
16	171.7	2.1	1.7	4.2	
17	608				

4. Heat Exchanger For ARC Blanket.

Initial values of the dimensions and number of the pipes:

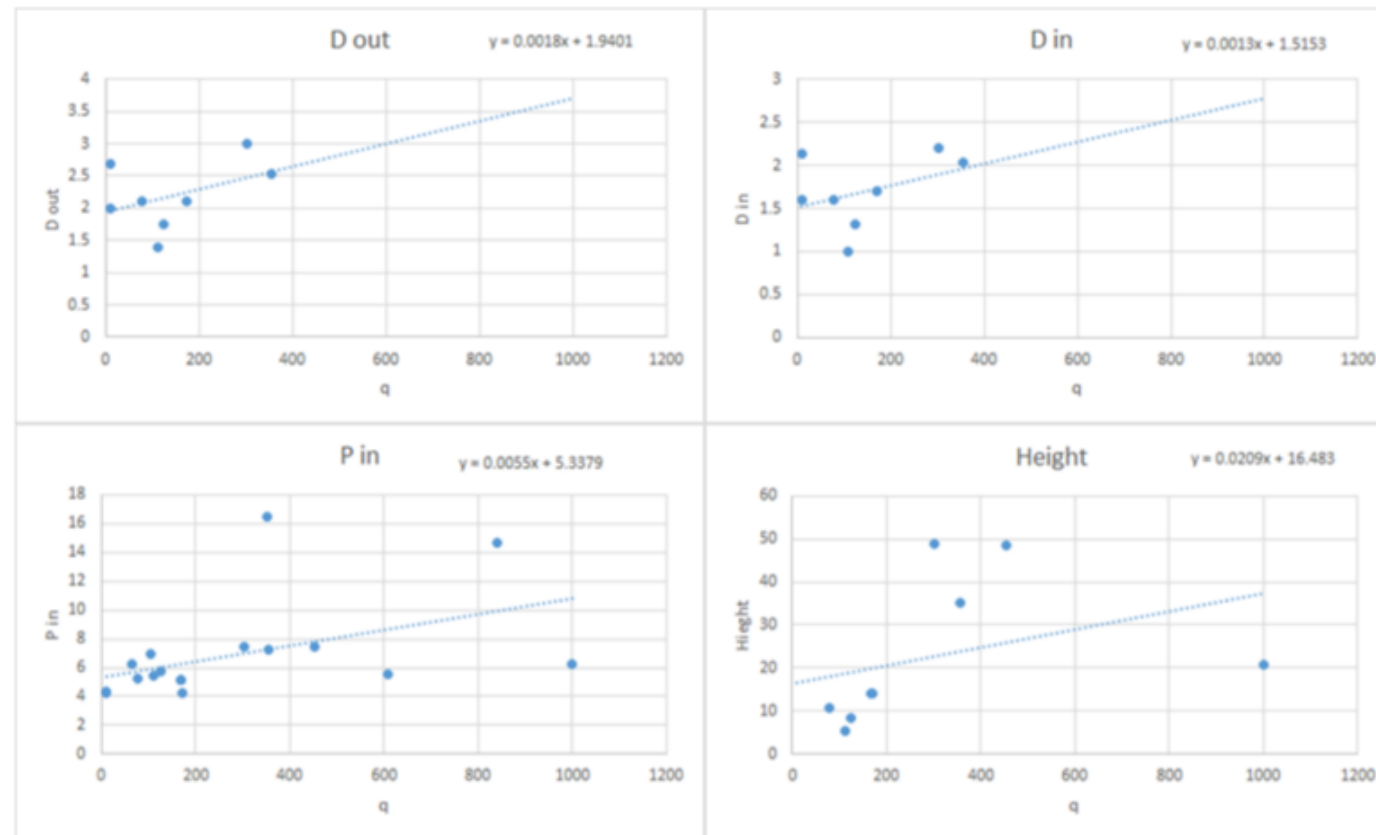


Figure 4.4: The average pipes dimensions and Helium pressure

4. Heat Exchanger For ARC Blanket.

Initial values of the dimensions and number of the pipes:

At power = 241.5 Mw:

- The outer diameter of the pipes = 2.3748 cm.
- The inner diameter of the pipes = 1.82925 cm.
- The Helium presser = 6.66615 M pascal.
- The length of the pipes = 21.53035 m.

4. Heat Exchanger For ARC Blanket.

Governing equations:

Heat Exchanger Equations

$$LTMD = \frac{(T_{h,out} - T_{c,in}) - (T_{h,in} - T_{c,out})}{\ln\left(\frac{T_{h,out} - T_{c,in}}{T_{h,in} - T_{c,out}}\right)} \quad (23)$$

$$A = \frac{Q}{U_{out,assumed} \times LTMD} \quad (24)$$

$$n = \frac{A}{\pi \times D_{out} \times L} \quad (25)$$

$$\text{Helium mass flow rate (m}'_{\text{He}}) = \frac{Q}{C_{p,He} \times (T_{c,out} - T_{c,in}) \times n} \quad (26)$$

4. Heat Exchanger For ARC Blanket.

Governing equations:

$$V_{He} = \frac{m'_{He}}{\rho_{He} \times \pi \times \left(\frac{D_{out}}{2}\right)^2} \quad (27)$$

$$Re_{in} = \frac{\rho_{He} \times V_{He} \times D_{in}}{\mu_{He}} \quad (28)$$

$$Nu_{in} = 0.023 \times Pr_{in}^{0.4} \times Re_{in}^{0.8} \quad (29)$$

$$h_{in} = \left(\frac{K_{He}}{D_{in}}\right) \times Nu_{in} \quad (30)$$

$$V_{max} = \frac{S_T}{S_T - D_{out}} \times V_{FLiBe},$$

where the distance between the center of two adjacent pipes (S_T) = $1.3 \times D_{out}$. (31)

4. Heat Exchanger For ARC Blanket.

Governing equations:

$$Re_{out} = \frac{\rho_{FLiBe} \times V_{max} \times D_{out}}{\mu_{FLiBe}} \quad (32)$$

•

$$\overline{Nu}_{out} = C_1 \times C_2 \times Re_{out}^m \times Pr_{FLiBe}^{0.36} \times \left(\frac{Pr}{Pr_s}\right)^{0.25},$$

where: $C_1 = 0.27$, $C_2 = 1$, $m = 0.63$ (33)

$$\overline{h}_{out} = \left(\frac{K_{FLiBe}}{D_{in}}\right) \times \overline{Nu}_{out} \quad (34)$$

$$U_{out, calculated} = \frac{1}{\frac{A_{out}}{A_{in} \times h_{in}} + \frac{A_{out} \times \ln\left(\frac{r_{out}}{r_{in}}\right)}{2 \times \pi \times K \times L} + \frac{1}{h_{out}}} \quad (35)$$

- If $\frac{U_{out, calculated} - U_{out, assumed}}{U_{out, assumed}} \times 100 < 30\%$, the dimensions are accepted. (36)
 - If $(S_T)^2 \times n \leq 0.1\text{m} \times 2.5\text{ m} = 0.25\text{ m}^2$, the dimensions are accepted. (37)

4. Heat Exchanger For ARC Blanket.

Computational model (MATLAB code):

1. Heat Exchanger

```
Command Window
>> Dout = 0.02;
Din = 0.017;
L = 15;
n = 180:5:400;
A = (pi*Dout*L).*n;
Up = (241500000*L/31.5)./((91.5198).*A);
m = (241500000*L/31.5)./((5195*340).*n);
v = m./(4.5809*pi*(Din/2)^2);
Rein = (4.5809*Din/(3.3217*((10)^(-5)))).*v;
hin = (0.2613*0.023*((0.65)^0.4)/Din).*((Rein).^0.8);
Reout = (4.333*1940*0.325/0.006).*Dout;
hout = ((1.1*0.27*((16)^0.36))./Dout).*((Reout).^0.63);
Uout = 1./((1./hout)+((Dout/Din)./hin)+((Dout/45)*log(Dout/Din)));
percentage = Uout ./ Up;
Uin = 1./(((Din/Dout)./hout)+(1./hin)+((Din/45)*log(Dout/Din)));
plot(n,percentage,'b--')
grid on
title('Determining the number of pipes at U = U out')
xlabel('The number of pipes')
ylabel ('The percentage = U out / U')
fx >>
```

4. Heat Exchanger For ARC Blanket.

Results and discussion:

1. Heat Exchanger

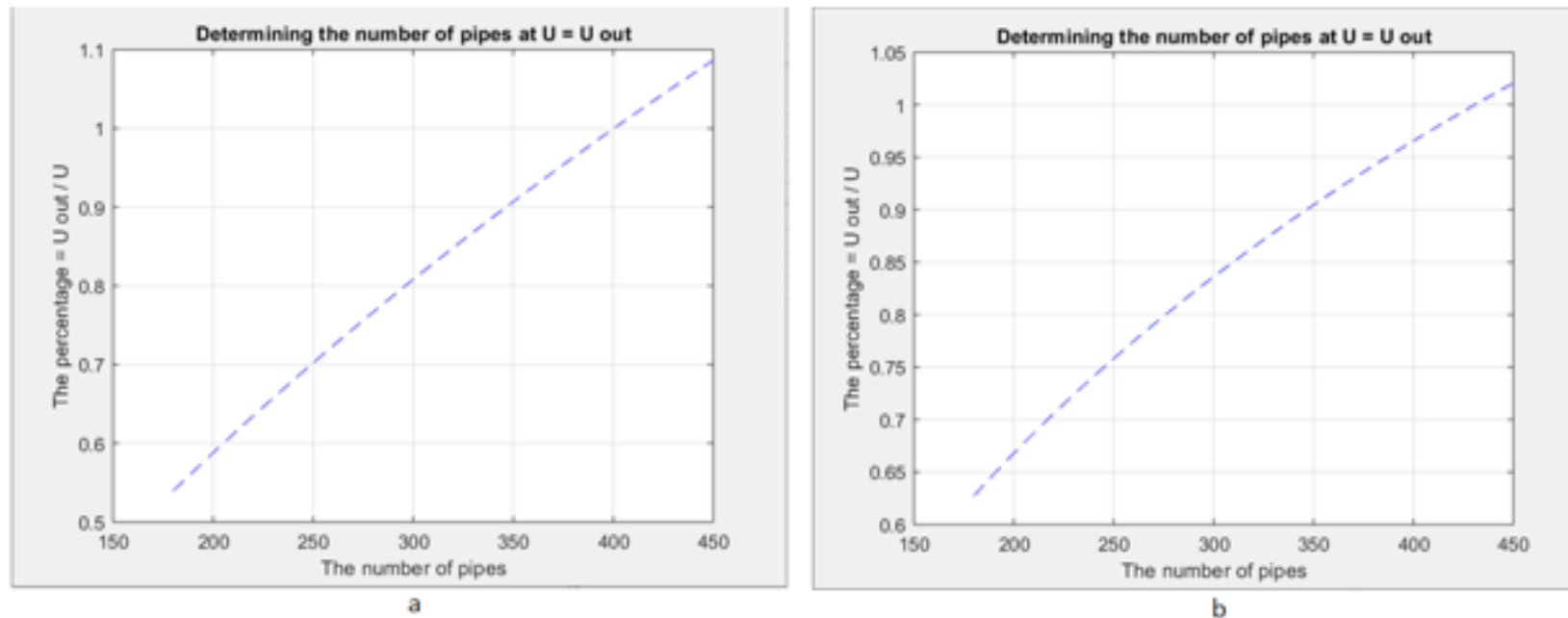


Figure 4.7: The effect of changing pipes outer diameter on the number of pipes at constant thickness and length (a) When $D_{out} = 0.015$ m, $D_{in} = 0.012$ m and $L = 15$ m.
(b) When $D_{out} = 0.03$ m, $D_{in} = 0.027$ m and $L = 15$ m.

4. Heat Exchanger For ARC Blanket.

Results and discussion:

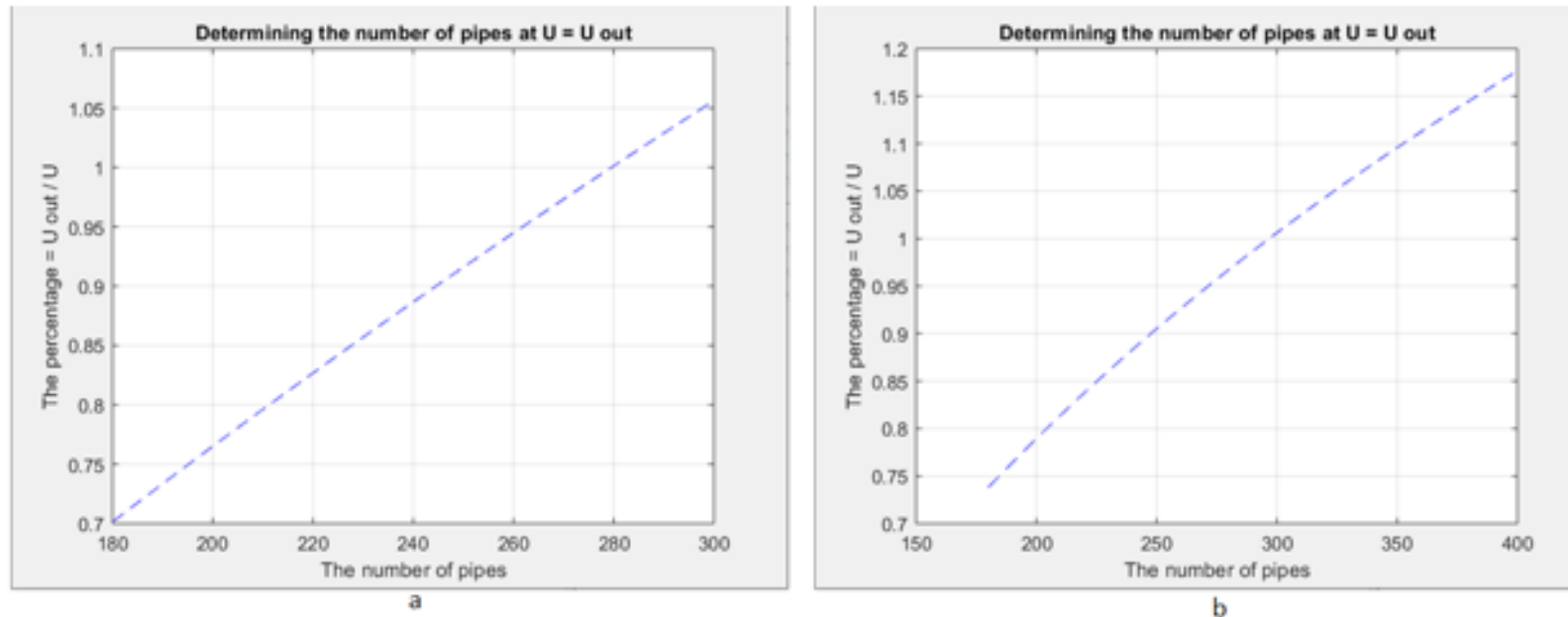


Figure 4.8: (a) The effect of changing pipes length on the number of pipes at constant thickness and diameter, when $D_{out} = 0.02$ m, $D_{in} = 0.017$ m and $L = 31.5$ m.
(b) The effect of changing pipes thickness on the number of pipes at constant length and diameter, when $D_{out} = 0.02$ m, $D_{in} = 0.019$ m and $L = 15$ m.

4. Heat Exchanger For ARC Blanket.

Results and discussion:

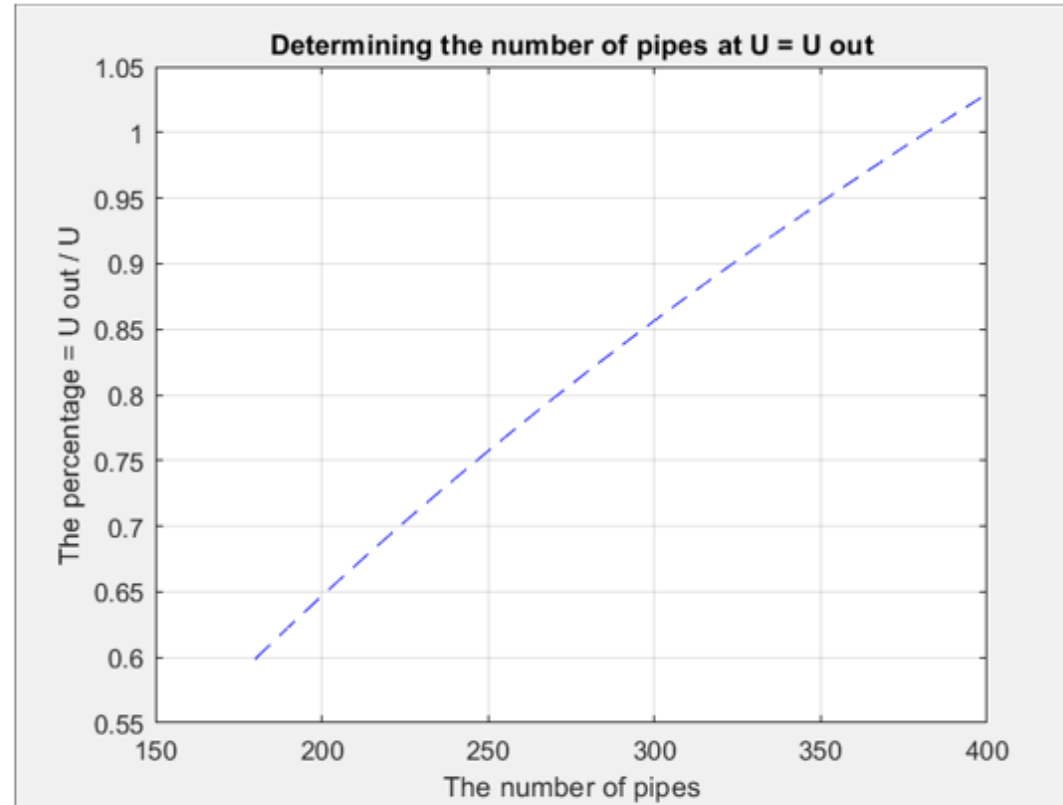


Figure 4.6: The number of pipes = 385, when $D_{out} = 0.02$ m, $D_{in} = 0.017$ m and $L = 15$ m.

4. Heat Exchanger For ARC Blanket.

Results and discussion:

- Figures 4.6, 4.7, and 4.8 show that when the dimensions are $D_{out} = 0.02$ m, $D_{in} = 0.019$ m, $L = 31.5$, and the number of pipes will be the lowest required number to transfer 241.5MW to be at the allowed space.
- Because of stress analysis on the pipe material, $D_{in} = 0.017$ m.
- Due to our computational power, The results will not be accurate at using $L = 31.5$ m, so the used length of the pipes will be equal to 15m.
- It was found at this design that the number of pipes = 385, and Helium inlet velocity = 165m/s.

4. Heat Exchanger For ARC Blanket.

Governing equations:

Stress Analysis Equations

- Because of $\frac{D_{out}}{2 \times \text{Thickness}} = \frac{0.017}{2 \times 0.0015} = 5.6667 < 10$, It is thick-walled cylinder. (38)

$$\sigma_t = \frac{P_i \times r_i^2 - P_o \times r_o^2 + \left(\frac{r_i^2 \times r_o^2}{r^2}\right) \times (P_i - P_o)}{r_o^2 - r_i^2} \quad (39)$$

$$\sigma_r = \frac{P_o \times r_o^2 - P_i \times r_i^2 + \left(\frac{r_i^2 \times r_o^2}{r^2}\right) \times (P_i - P_o)}{r_o^2 - r_i^2} \quad (40)$$

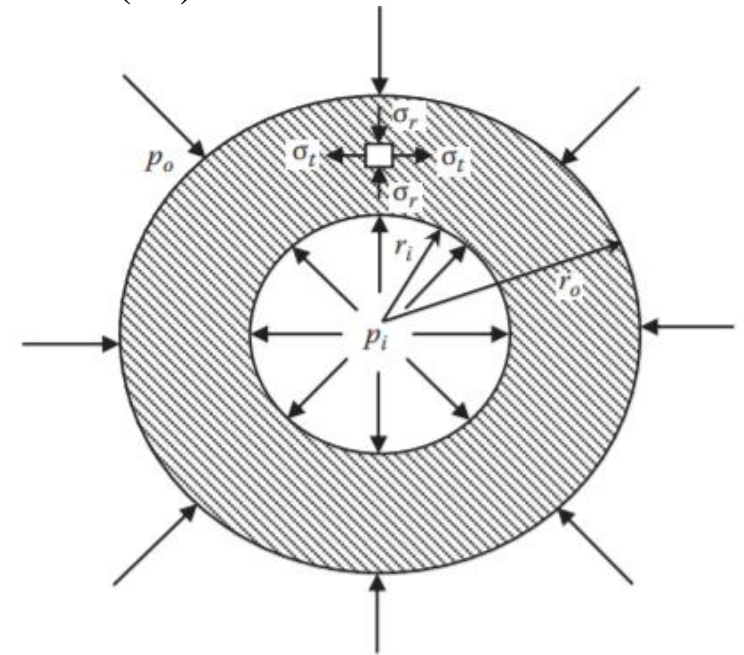


Figure 4.5: Thick-walled cylinder.

4. Heat Exchanger For ARC Blanket.

Computational model (MATLAB code):

2. Stress Analysis

```
Command Window
>> Pin = 6;
Pout = 0.0007;
Rin = 0.017/2;
Rout = 0.02/2;
R = 0.017/2:0.001:0.02/2;
TheRadialStress = ((Pout*(Rout^2))-(Pin*(Rin^2))+(((Rin^2)*(Rout^2)*(Pin-Pout))./(R.^2)))/((Rout^2)-(Rin^2));
TheTangentialStress = ((Pin*(Rin^2))-(Pout*(Rout^2))+(((Rin^2)*(Rout^2)*(Pin-Pout))./(R.^2)))/((Rout^2)-(Rin^2));
plot(R,TheRadialStress,'b--',R,TheTangentialStress,'r--')
grid on
legend ('The Radial Stress','The Tangential Stress')
title ('Thick-Walled Cylinder')
xlabel('Radius')
ylabel ('Stress')
fx >>
```

4. Heat Exchanger For ARC Blanket.

Results and discussion:

2. Stress Analysis

Figure 4.9 shows that the maximum stress = 37.5 Mpa < Inconel718 yield stress at 900 K = 800 M pa. So, this design is acceptable at stress analysis point of view.

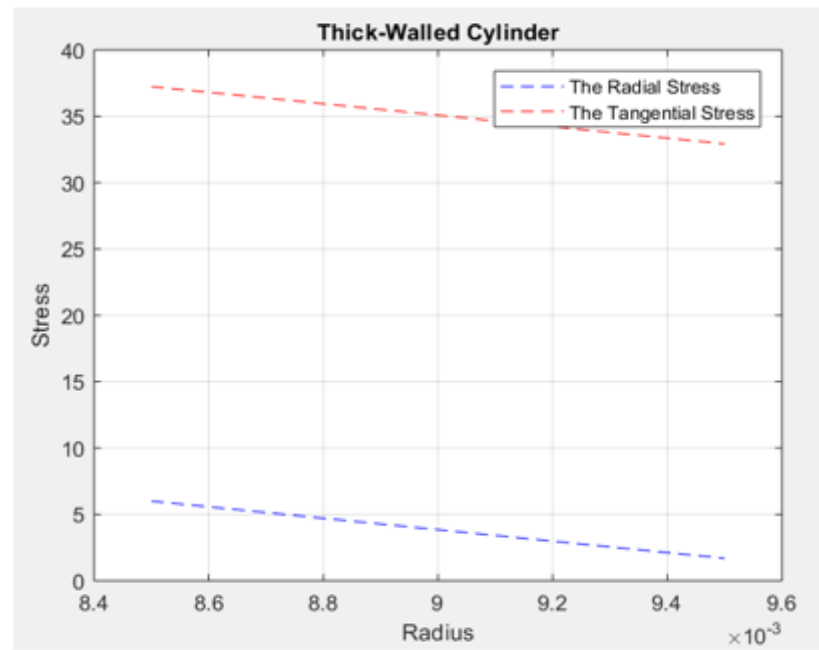


Figure 4.9: The stress on the pipes.

4. Heat Exchanger For ARC Blanket.

Verification model:

- Ansys software simulation was made to verify the design of the determined heat exchanger.
- Because of computing power, simulating just one pipe was chosen ($D_{out} = 0.02 \text{ m} \times D_{in} = 0.017 \text{ m} \times L = 15 \text{ m}$) at the center of a box ($8 \text{ cm} \times 8 \text{ cm} \times 15 \text{ m}$).
- The properties of FLiBe and Helium was chosen to change with temperature.
- The simulation was at turbulent viscosity with Standard k- ϵ model.
- The two FLiBe velocities 0.325 m/s and 0.259 m/s were run.
- Three different meshes were run to test the mesh dependency.

4. Heat Exchanger For ARC Blanket.

Verification model:

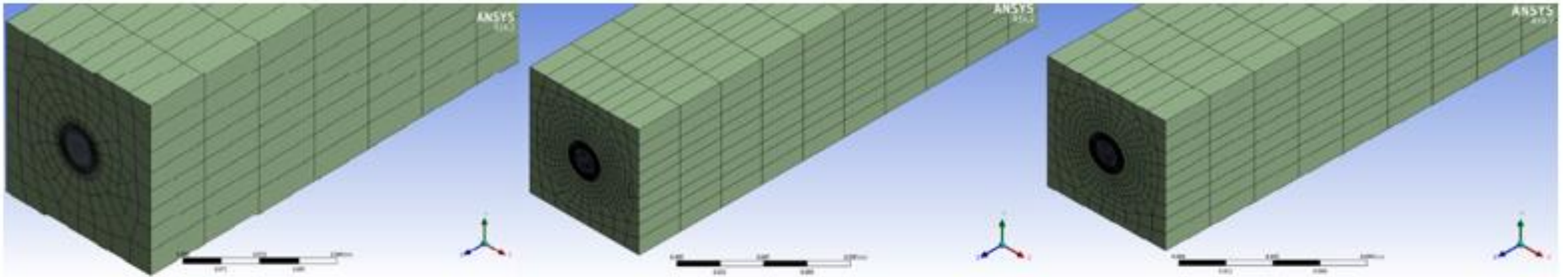


Figure 4.10: A) Mesh with 333500 elements b) Mesh with 595468 elements. c) Mesh with 631441 elements.

4. Heat Exchanger For ARC Blanket.

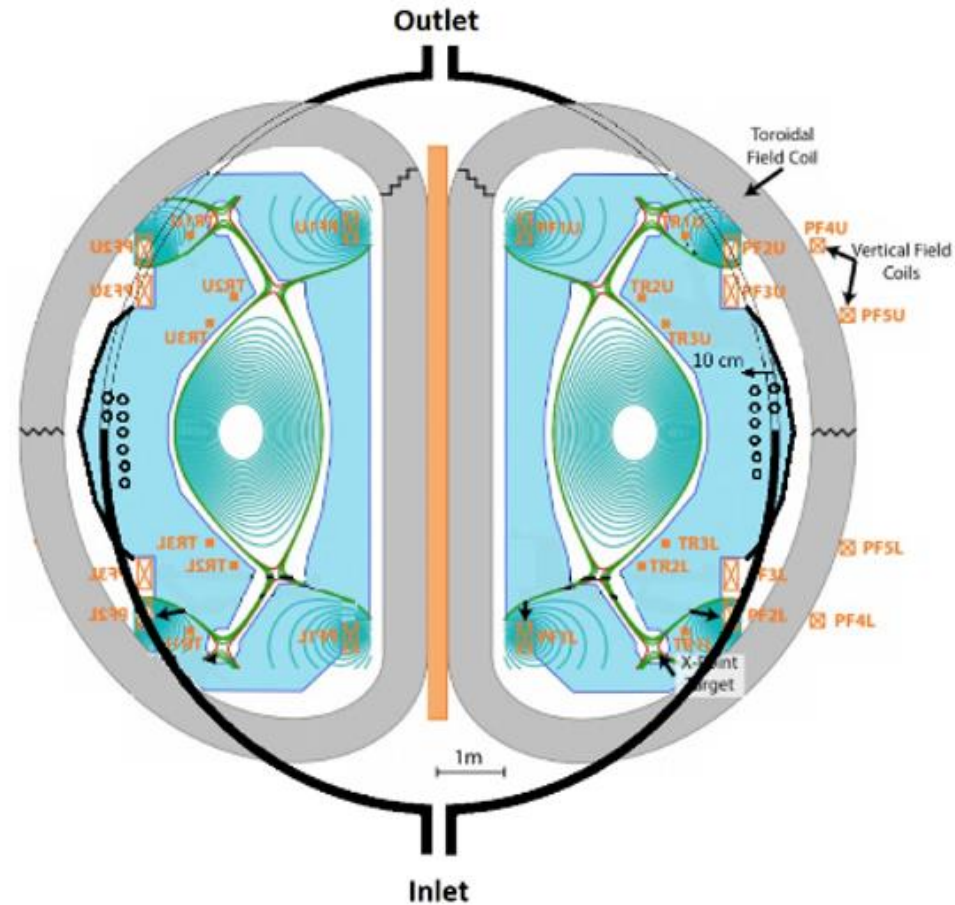
Verification model:

Table 4.2: Comparison between different simulations.

Characteristics	Mesh = 333500 element		Mesh = 595468 element		Mesh = 632441 element	
	$V_{\text{FLiBe}} =$ 0.325 m/s	$V_{\text{FLiBe}} =$ 0.259 m/s	$V_{\text{FLiBe}} =$ 0.325 m/s	$V_{\text{FLiBe}} =$ 0.259 m/s	$V_{\text{FLiBe}} =$ 0.325 m/s	$V_{\text{FLiBe}} =$ 0.259 m/s
Helium average outlet temperature (K)	823.79	821.87	827.701	826.97	831.05	828.92
Total heat flow rate to Helium for one pipe (w)	352362.8	350274.8	260763.2	360249.3	364807.2	362438.4
Number of pipes required to transfer 241.5 Mw	688	696	672	672	664	672
Pumping power for one pipe (w)	76211.67	75909.72	81393.58	79144.69	82396.29	83559.15
Pumping power for all pipe (Mw)	52.474	52.833	54.696	53.185	54.711	56.151
The efficiency	78.27%	78.12%	77.35%	77.97%	77.34%	76.74%

4. Heat Exchanger For ARC Blanket.

Verification model:



4. Heat Exchanger For ARC Blanket.

Conclusion:

It was concluded that the optimized design of the heat exchanger for ARC fusion reactor is when:

- I. each half of the tokamak will contain approximately 388 pipes (4 columns of pipes beside each other and 97 rows from pipes above each other)
 - II. with dimensions ($D_{out} = 0.02 \text{ m} \times D_{in} = 0.017 \text{ m} \times L = 15 \text{ m}$) as shown at Figure 4.11.
- From the results shown in the table 6.2, This design of heat exchanger for ARC blanket is capable of transferring thermal power = **241.5MW** from ARC blanket with efficiency = **77.97%**.

Thanks