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"Numerical Analysis for Optimization of Circulation Power in First Wall of Indian Helium Cooled Solid Breeder Blanket using He-CO_2 Gas Mixture"

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Outline

- Introduction
- First Wall of HCSB
- Comparison of various gas coolants
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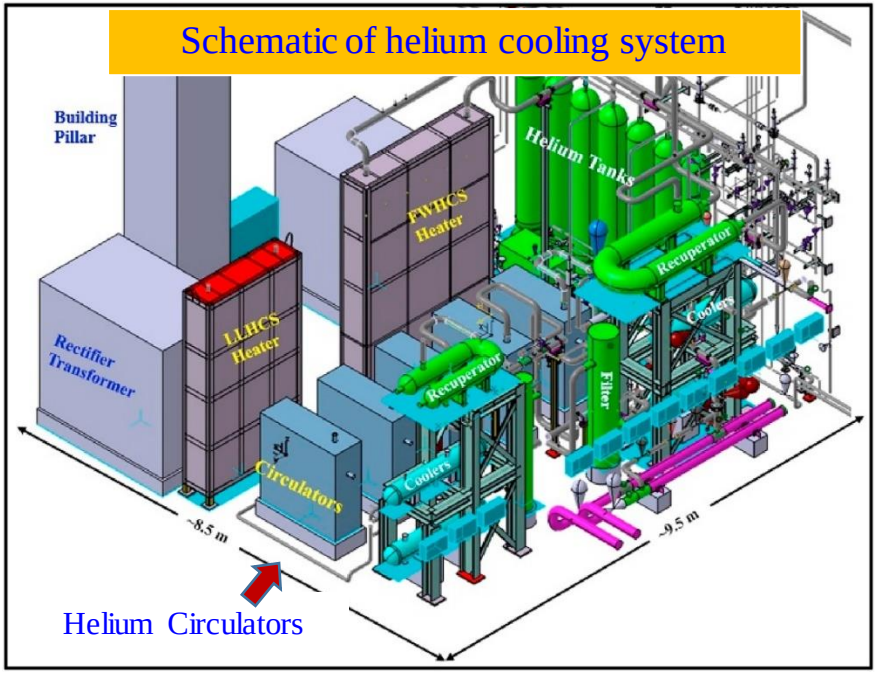
- Objectives
- Thermal-Hydraulic analysis of single channel of FW
- Thermal analysis of 5 channels of FW
- Conclusions

Introduction

Helium Gas has found applications in cooling systems of High Temperature Gas cooled Reactor (HTGR), breeding blankets of ITER and DEMO reactors due to its good transport and thermal properties. **A major disadvantage of Helium is its extremely low density, which requires high input circulation power for circulator**

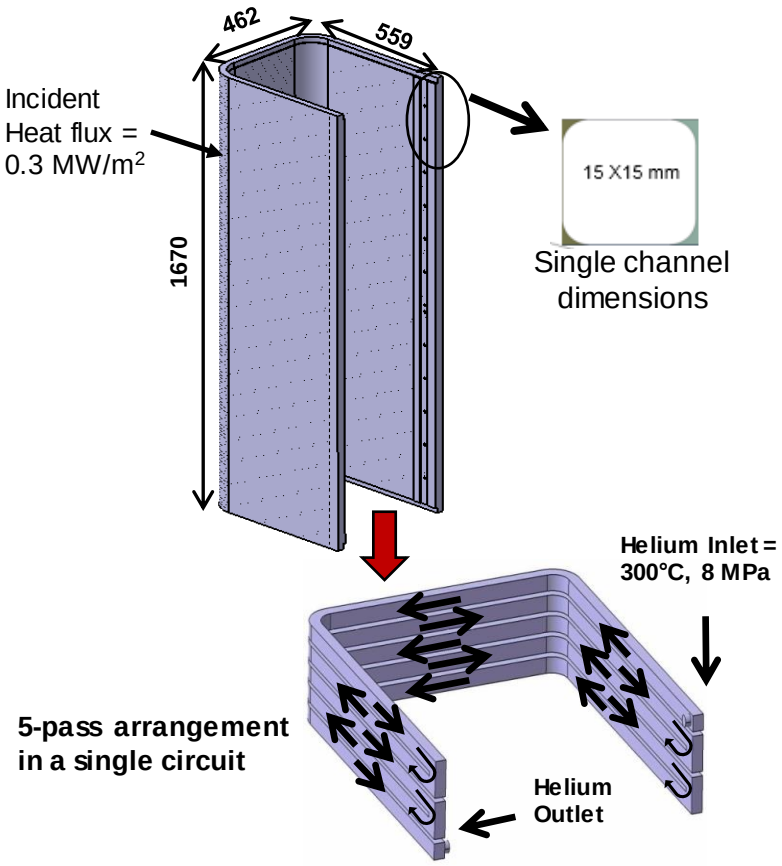
For a 300 kW rated heat removal capacity of helium cooling system of Indian breeding blanket, **the input circulation power is ~ 120 kW (per circulator)** at a compression ratio of 1.16



Reference: Helium cooling systems for Indian LLCB TBM testing in ITER, B.K.Yadav et al;, FED, Vol. 124, 2017, 710-718

Details of First Wall of Indian Helium Cooled Solid Breeder (HCSB)

Layout of FW structure actively cooled by Helium



- Material of Construction (FW): Ferritic-Martensitic Steel
- Permissible FW material temperature: 550 C
- Total no. of channels: 80
- Number of circuits: 16
- Number of channels per circuit: 5
- Channel dimension: 15x15 mm (for all 80 channels)
- Helium gas velocity: ~ 50 m/s
- Helium mass flow: 1kg/s

FW mockup in tested in HELOKA, KIT

- FW mock-up **(Total 10 channels in 2 circuits)** fabricated in India was tested with Helium gas in HELOKA test facility at KIT, Germany
- *Ref: S. Ranjith Kumar et al; "Performance assessment of the Helium cooled First Wall mock-up in HELOKA facility", Fusion Engineering and Design, 2020, 150, 1-13*

Helium Circulator of EHCL

- 2-stage centrifugal turbo machine
- P_{in}/P_{out} = 78 bar/ 83 bar
- Power = 30 kW
- Flow rate = 225 g/s
- Design temp. = 100 °C
- Design pressure = 100 bar
- *Ref: P. Chaudhuri et al; "Status and progress of Indian LLCB test blanket systems for ITER", Fusion Science and Technology, 2020, 150, 1-7*

Comparison of Various Gas Coolants

Thermo-physical Properties Comparison of Gas coolants at 700 K and 8 MPa

Parameters	He	Xe	Kr	Ar	CO_2
Molecular weight (g/mole)	4.003	131.29	83.80	40	44
Density (kg/m^3)	5.43	181.70	113.50	53.75	60.45
Thermal conductivity (W/m-k)	0.285	0.0126	0.0196	0.0354	0.051
Dynamic viscosity (Pa-s)	$3.6x10^{-5}$	$5.0x10^{-5}$	$5.1 x10^{-5}$	$4.4x10^{-5}$	$3.2x10^{-5}$
Heat capacity (kJ/kg-k)	5.19	0.173	0.259	0.532	1.167

- Helium gas has excellent thermal and transport properties among other gases
- Helium gas has lowest density
- Density of CO_2 gas more than 10 times than Helium

Replacement of Helium Coolant

- Circulation power (Pp) is defined as:

$$Pp \propto \frac{m^3}{\rho^2}$$ (m = mass flow rate and ρ = density of fluid)

- Helium gas has a disadvantage of low density which translates in high circulation power

- As per literature survey:
  - Circulation power is found to be reduced (9%-13%) when CO_2 mixed with Helium gas *

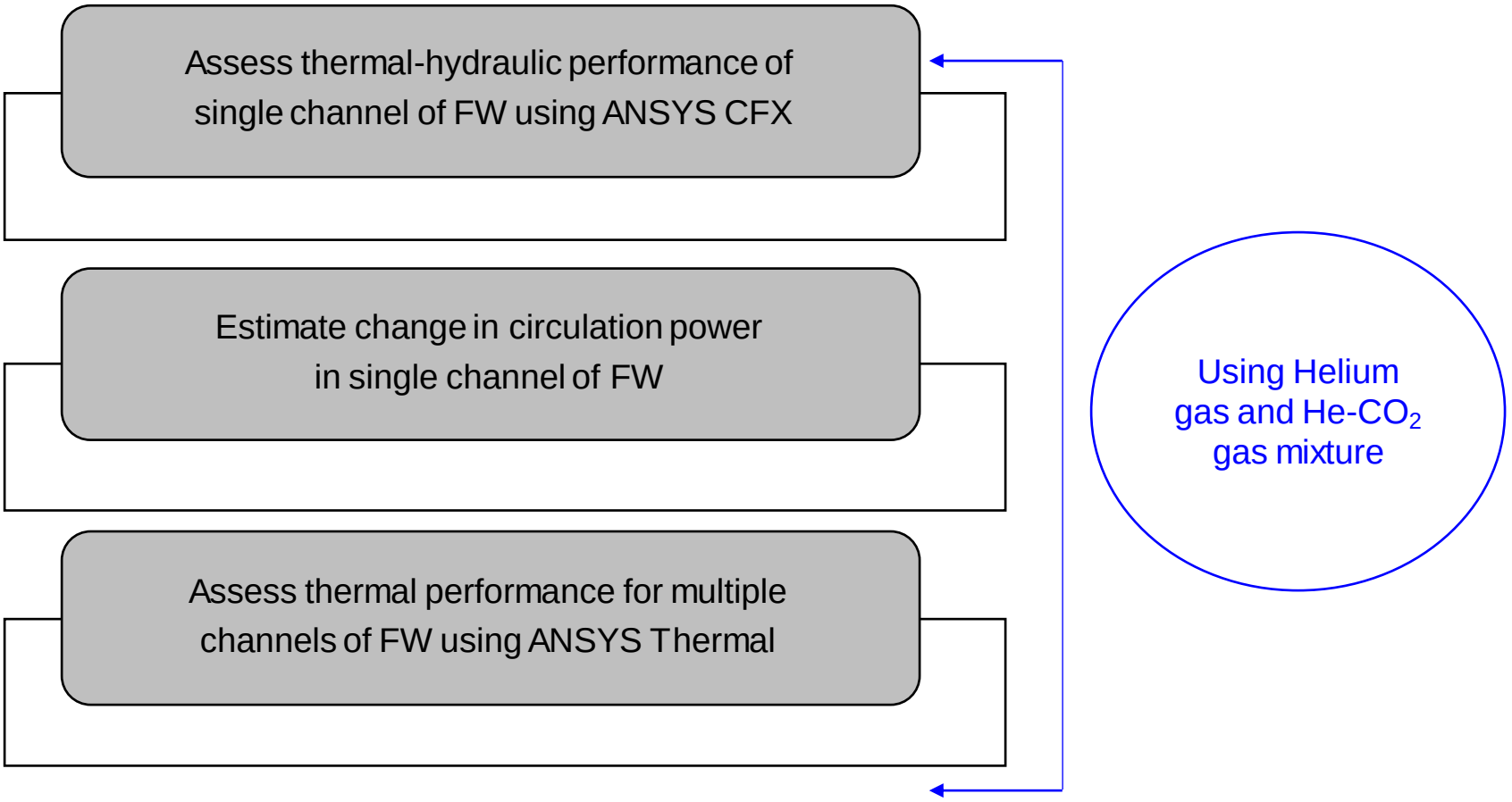
- CO_2 gas looks as the most promising to be mixed with pure Helium due to its high density, thermodynamically proven as coolant in high temperature reactors and abundant in nature

** References:*

1. "Reduction of circulation power for helium-cooled fusion reactor blanket using additive CO_2 gas" Yeon-Gun Lee et al; Fusion Engineering and Design, 2015, Page no. 436-442

2. "The Cooling Performance Improvement of First Wall Using He/CO_2 Binary Mixtures for CN HCCB TBM", Haifei Deng et al; Fusion Science and Technology, 72:2, Page no. 188-198

Objectives

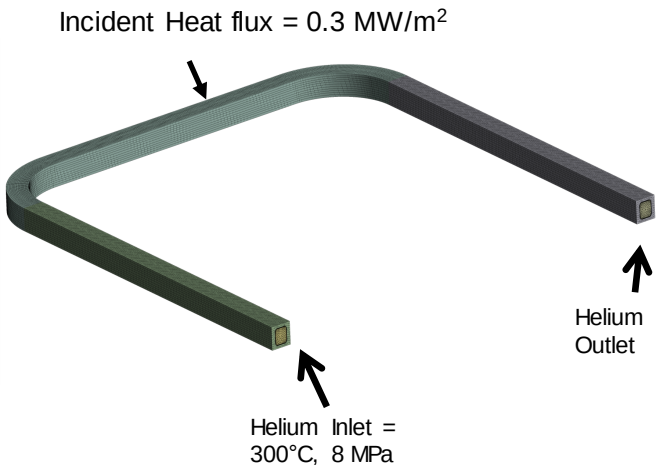

Assess thermal-hydraulic performance of single channel of FW using ANSYS CFX
Estimate change in circulation power in single channel of FW
Assess thermal performance for multiple channels of FW using ANSYS Thermal
Using Helium gas and He-CO_2 gas mixture

Assumptions and Input Parameters for Single Channel of FW

- Steady state operation and Average bulk temperature is calculated
- Side walls of FW doesn't receive heat flux i.e. adiabatic conditions
- Average Helium velocity assumed is 50 m/s

Input Parameters for Single Channel *

S.No.	Parameter	Value
1	Incident Heat Flux	0.3 MW/m^2
2	Neutronic heat generation	5.0 MW/m^2
3	Helium Inlet Temperature	300 °C
4	Helium Inlet Pressure	8 MPa
5	Helium flow rate	0.0125 kg/s
6	Channel dimensions	15 x 15 mm^2
7	Max. FW Temperature	550 °C

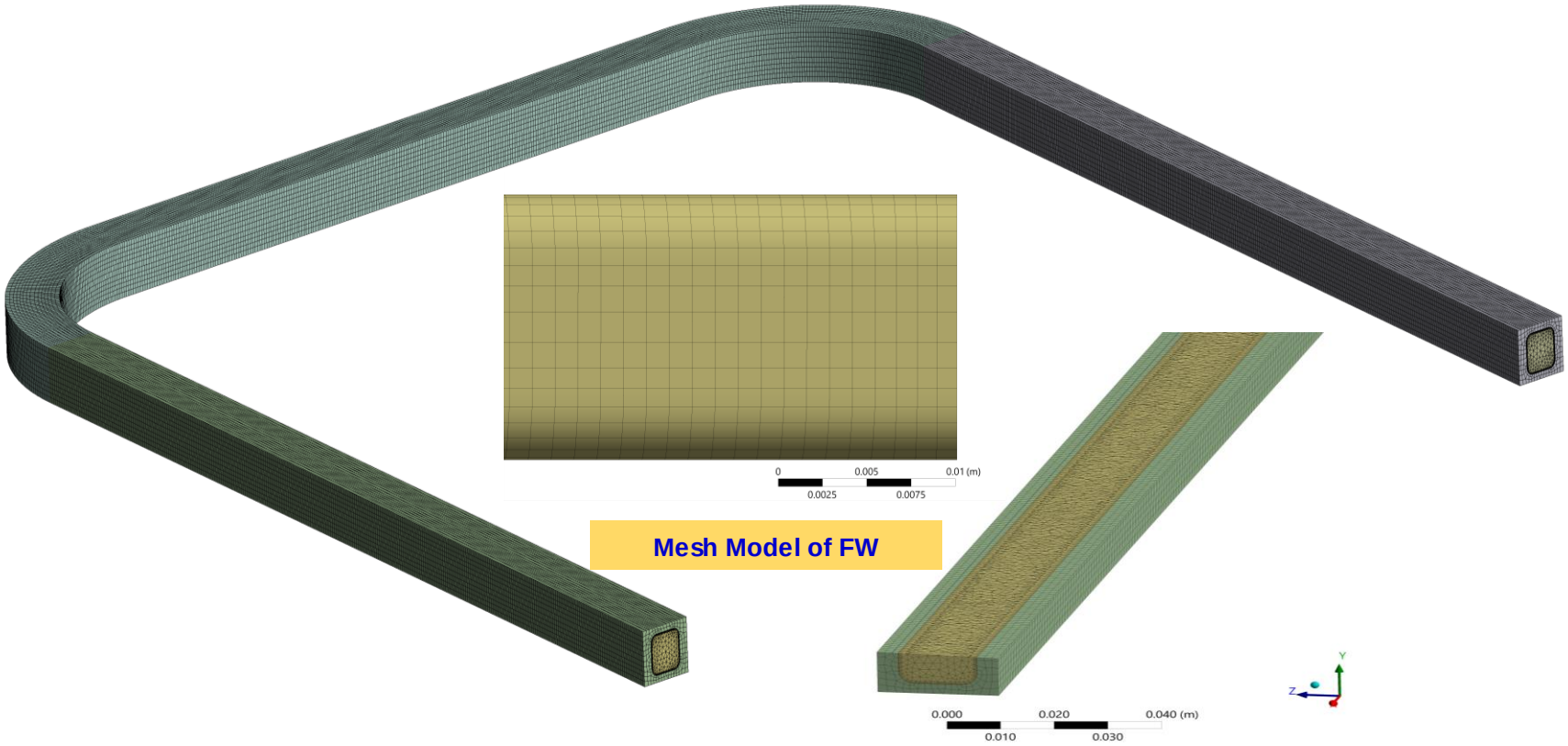


Mixture Ratio in %	He	100	90	80	70	60	50	40	30	20	10	0
	CO_2	0	10	20	30	40	50	60	70	80	90	100

** Deepak Sharma, et al; "Design update and thermal-hydraulics of LLCB TBM first wall", FED, 2018, Vol. 134, 51-61*

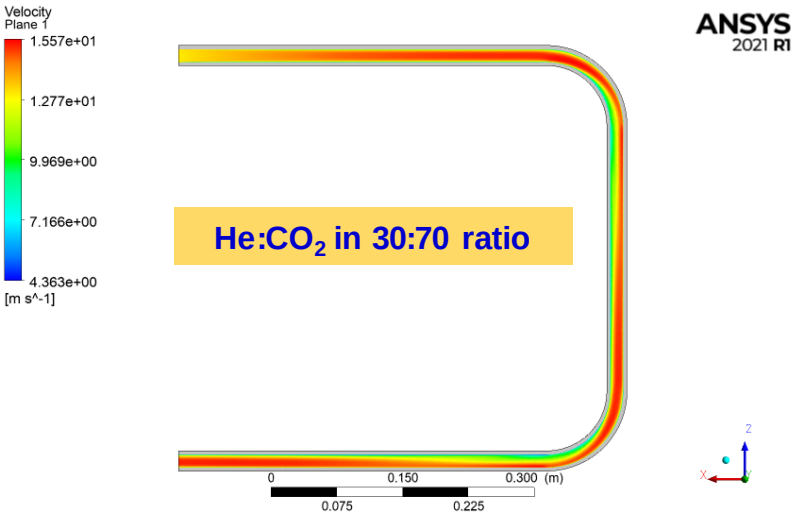
Modeling and Meshing of Single Channel of FW

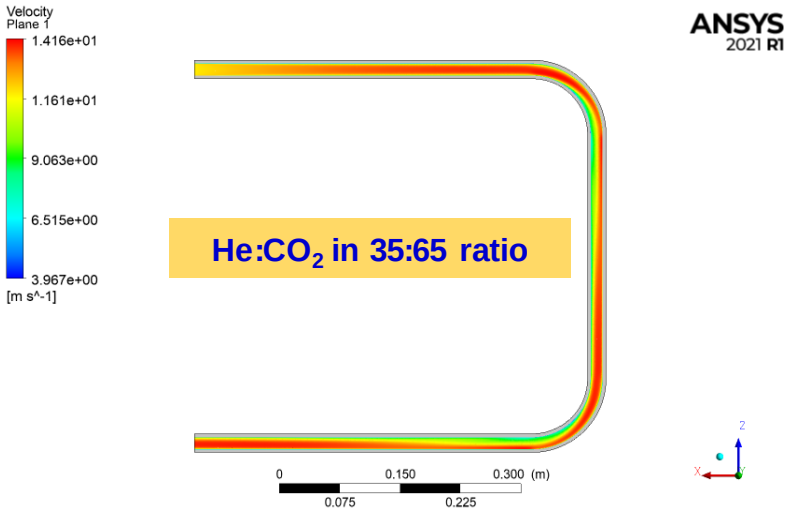
- Mesh size of channel body = 5 mm
- Mesh size of fluid path = 2 mm
- Skewness = 0.2, Aspect ratio = 1.099, Orthogonal = 0.6
- Total number of nodes and elements used are 6,22,095 and 13,52,669 respectively
- K-ξ based Turbulence model

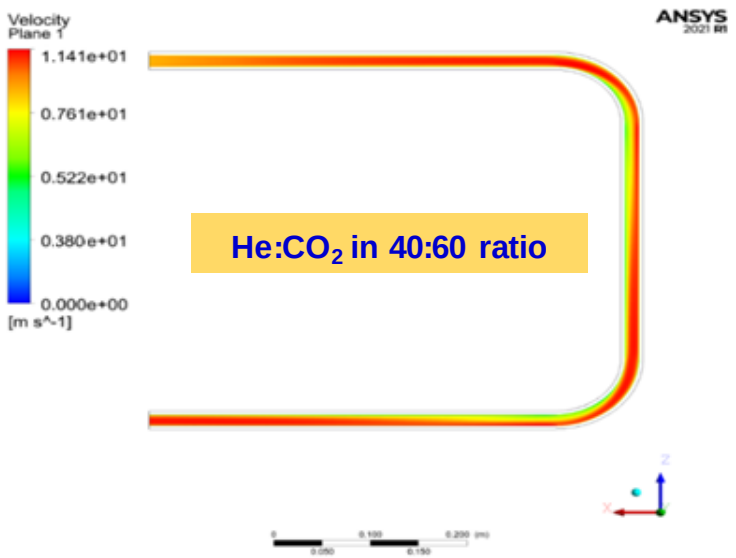


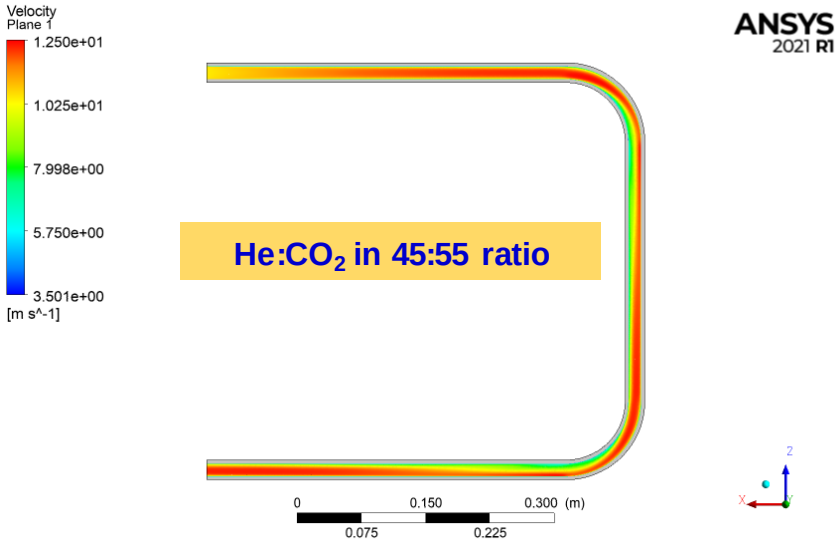
Mesh Model of FW

Velocity Distribution for Single Channel of FW (He-CO_2 Gas Mixture)

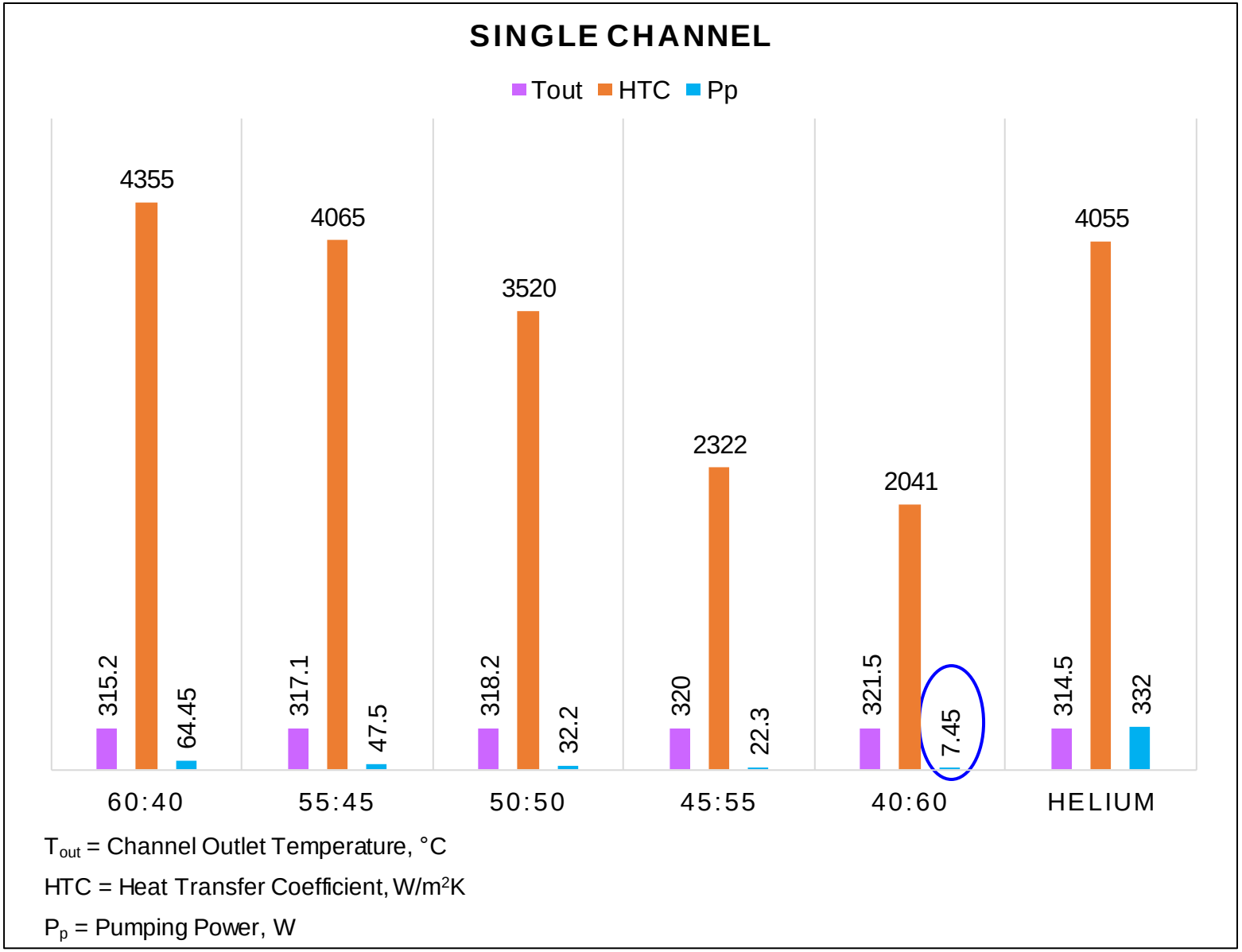








Thermo-Hydraulic Results for Single Channel of FW

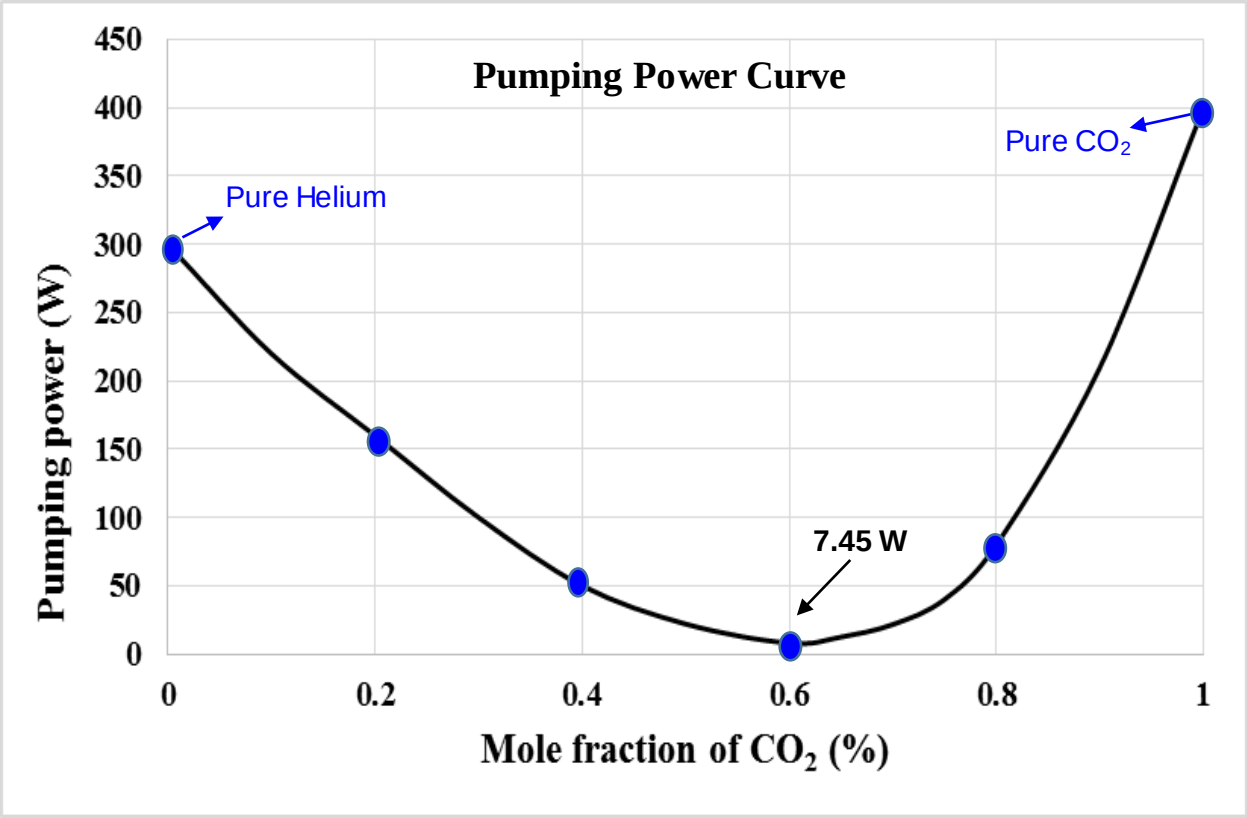


T_{out} = Channel Outlet Temperature, °C

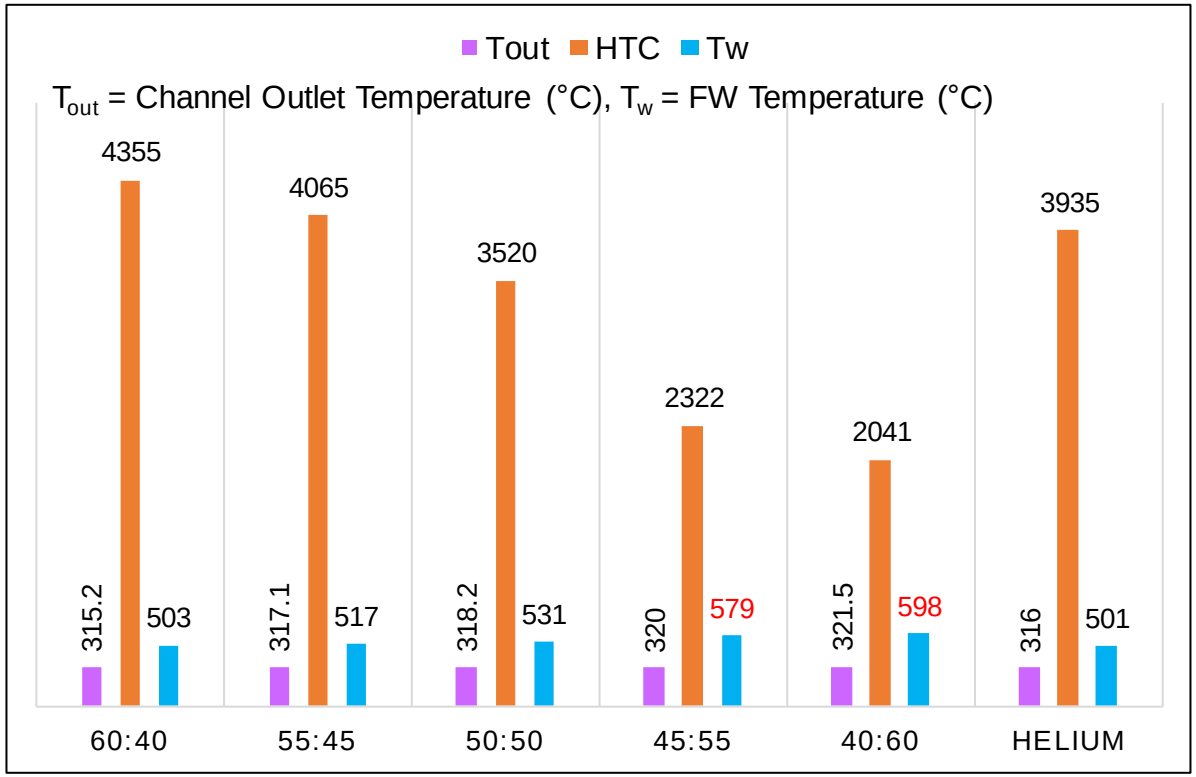
HTC = Heat Transfer Coefficient, W/m^{2}K

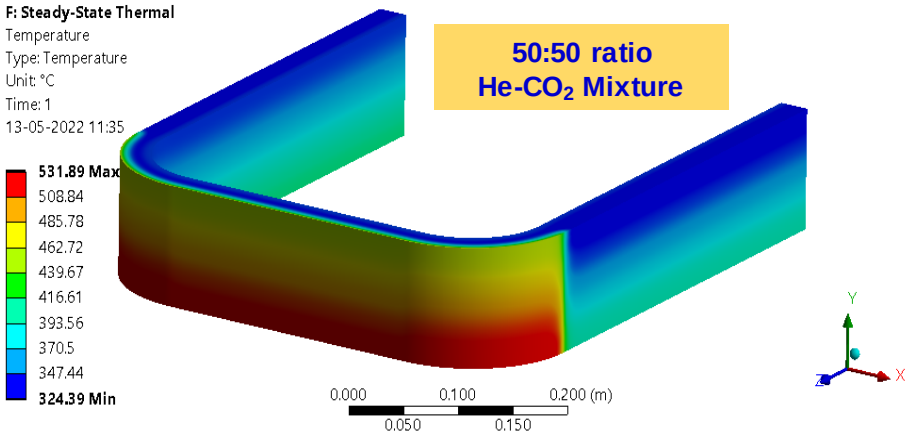
P_p = Pumping Power, W

Pumping power results for Single Channel of FW



Thermal Analysis Results for 5 Channels





Conclusions

- Min.circulation power of 7.45 W at 0.6 mole fraction of CO_2 gas in single channel of FW
- HTC values (3520-4355 W/m^2-K) at 0.4-0.5 mole fraction of CO_2 gas against pure Helium Gas
- FW material temperature (550 °C) exceeds for 0.5 mole fraction of CO_2 and beyond
- **An optimum mole fraction range of 0.4-0.5 of additive CO_2 gas in He-CO_2 mixture may be selected as primary coolant for heat extraction in FW**

Future Scope

- Detailed numerical Investigation of full scale FW mock-up using He-CO_2 gas mixture
- Development of indigenous circulator using He-CO_2 gas mixture as coolant
- Experimental investigation of He-CO_2 gas mixture for various channel mock-ups

THANK YOU