Design and Development of Sustainable Energy Harvesting System through Thermoelectric Generator and Vortex Tube (TeG-VT)

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ABSTRACT

- **Computational Fluid Dynamics (CFD)** analysis using ANSYS Fluent software is applied to simulate the flow behaviors in Straight and Curved Vortex Tubes under different inlet pressure conditions.
- Finite Element Simulations of **Thermoelectric Generator (TeG)** are performed using COMSOL software to predict the electric current flow under different temperature gradients
- Experimental setup of **TeG-VT system** is developed for ***sustainable energy harvesting*** and to validate simulation results
- Promising results, around 96 °C temperature difference and 520 mV from single TeG, are found

MOTIVATION

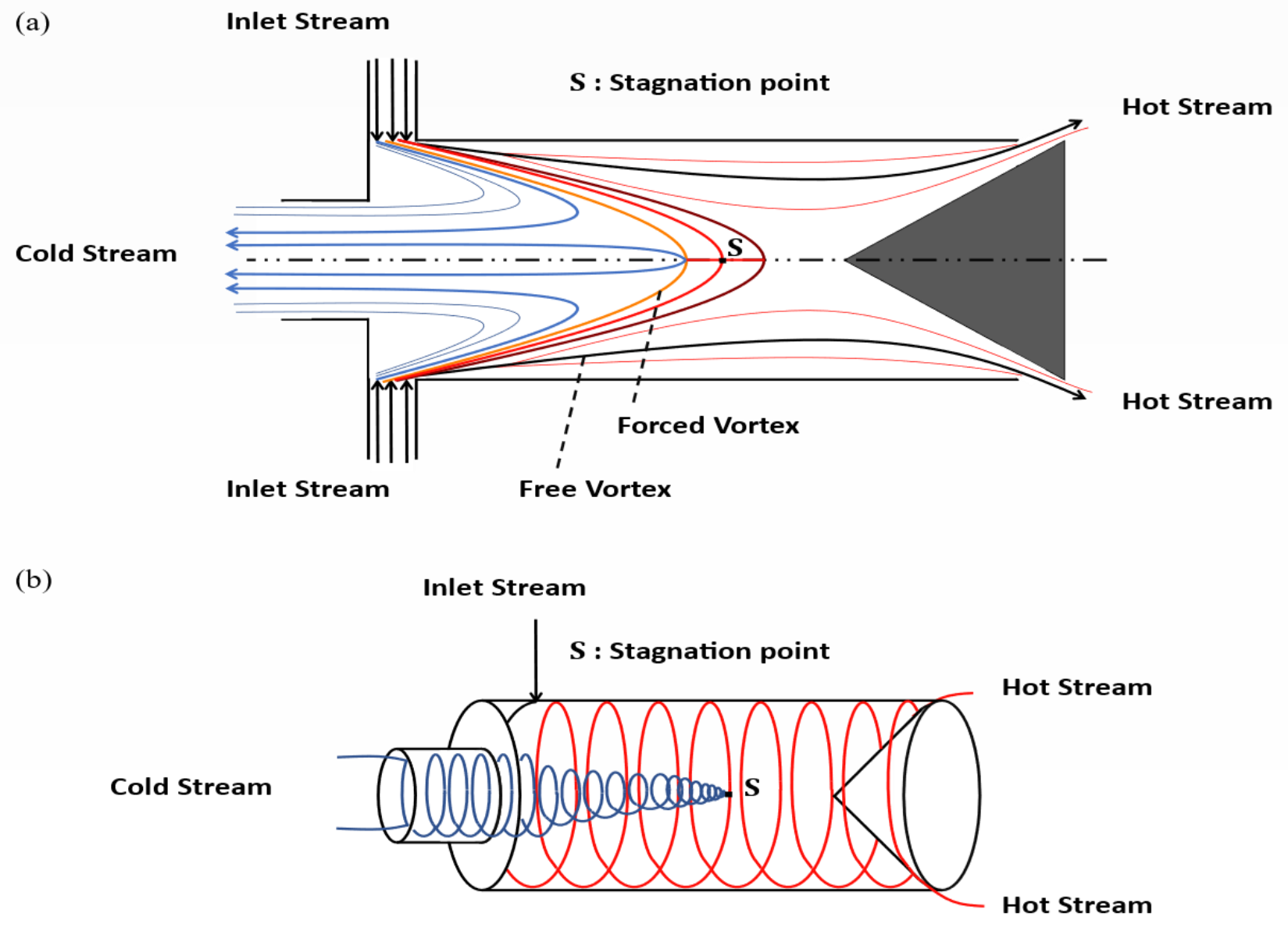
- **Energy storage** is one of the challenging and ambitious topics in the entire scientific and research community
- Multiple energy storing technologies are introduced in the past decades like batteries, long duration flywheels, high energy capacitors, and superconducting magnetic storage → ***sustainability is absent in many***
- **Vision 2030** projects hover around ***"Development of Sustainable Energy Resources"***

OBJECTIVES

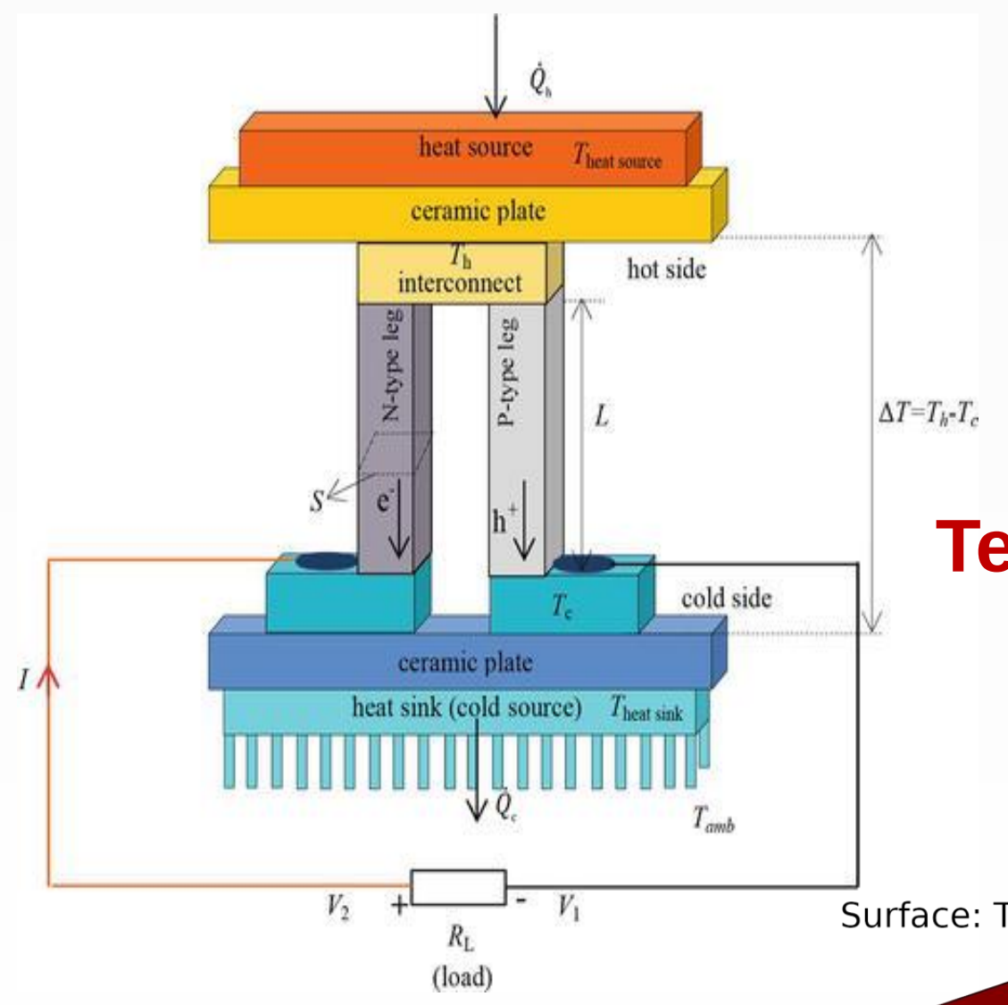
Main objective of this research is to ***design, fabricate, and test a TeG-VT system*** that can generate **sufficient power** to operate ***electronic sensor networks*** in low accessibility, hard to reach locations such as deep oil/gas/water wells, & spot cooling with energy harvesting in manufacturing process

VORTEX TUBE & TeG

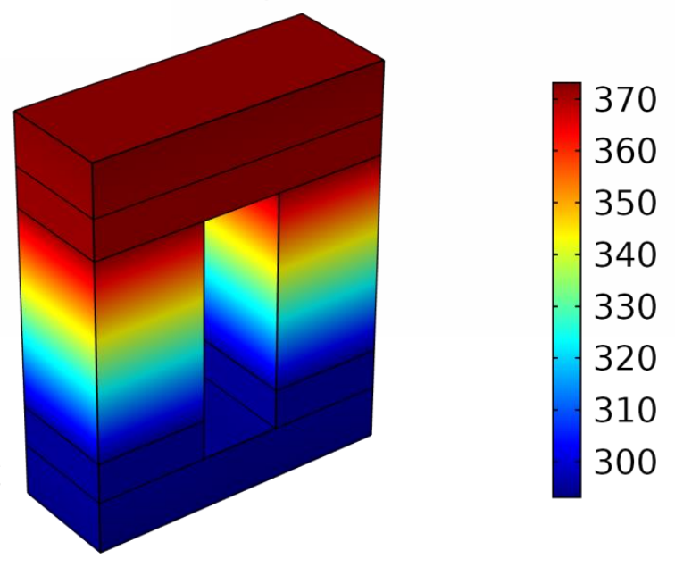
Vortex tube is a mechanical device that separates a compressed gas stream into hot and cold air streams without any moving parts [1]



TeGs are devices that convert heat energy directly into electrical energy using Seebeck effect, when two different conductive materials experience a temperature gradient



TeG schematic



Temperature distribution on TeG

MATHEMATICAL MODELING

CONSTITUTIVE EQUATIONS FOR CFD ANALYSIS

$$\frac{\partial(\rho v_i)}{\partial x_i}=0 \qquad \text{(Continuity equation)}$$

$$\frac{\partial(\rho v_i v_j)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial v_k}{\partial x_k}\right)\right]-\frac{\partial P}{\partial x_j}+\frac{\partial}{\partial x_j}\left(-\rho\overline{v_i' v_j'}\right) \qquad \text{(Navier−Stokes equation)}$$

$$\frac{\partial(\rho v_i k)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M \qquad \text{(Turbulence kinetic energy)}$$

$$\frac{\partial(\rho v_i \varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_3G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad \text{(Turbulence dissipation rate)}$$

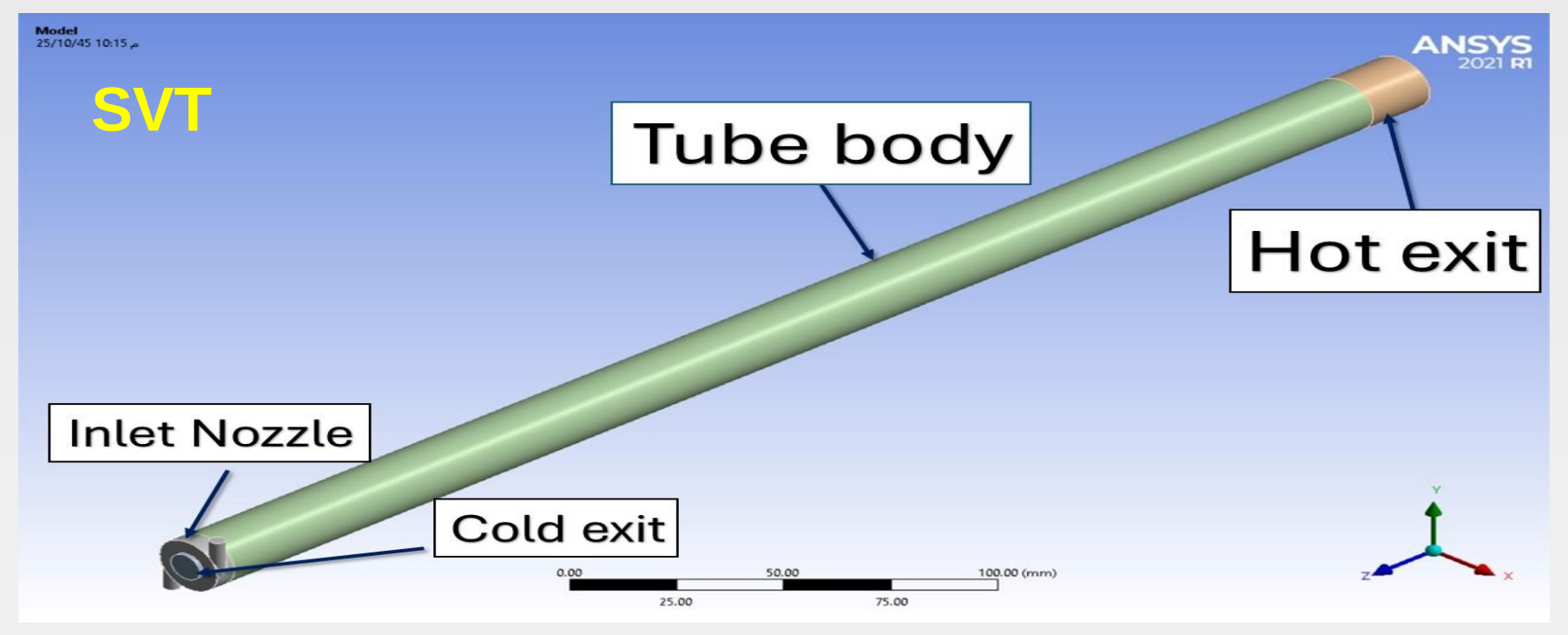
$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \qquad \text{(Turbulence dissipation rate)}$$

$$P=\rho RT \qquad \text{(Ideal gas law)}$$

FINITE ELEMENT MODELING

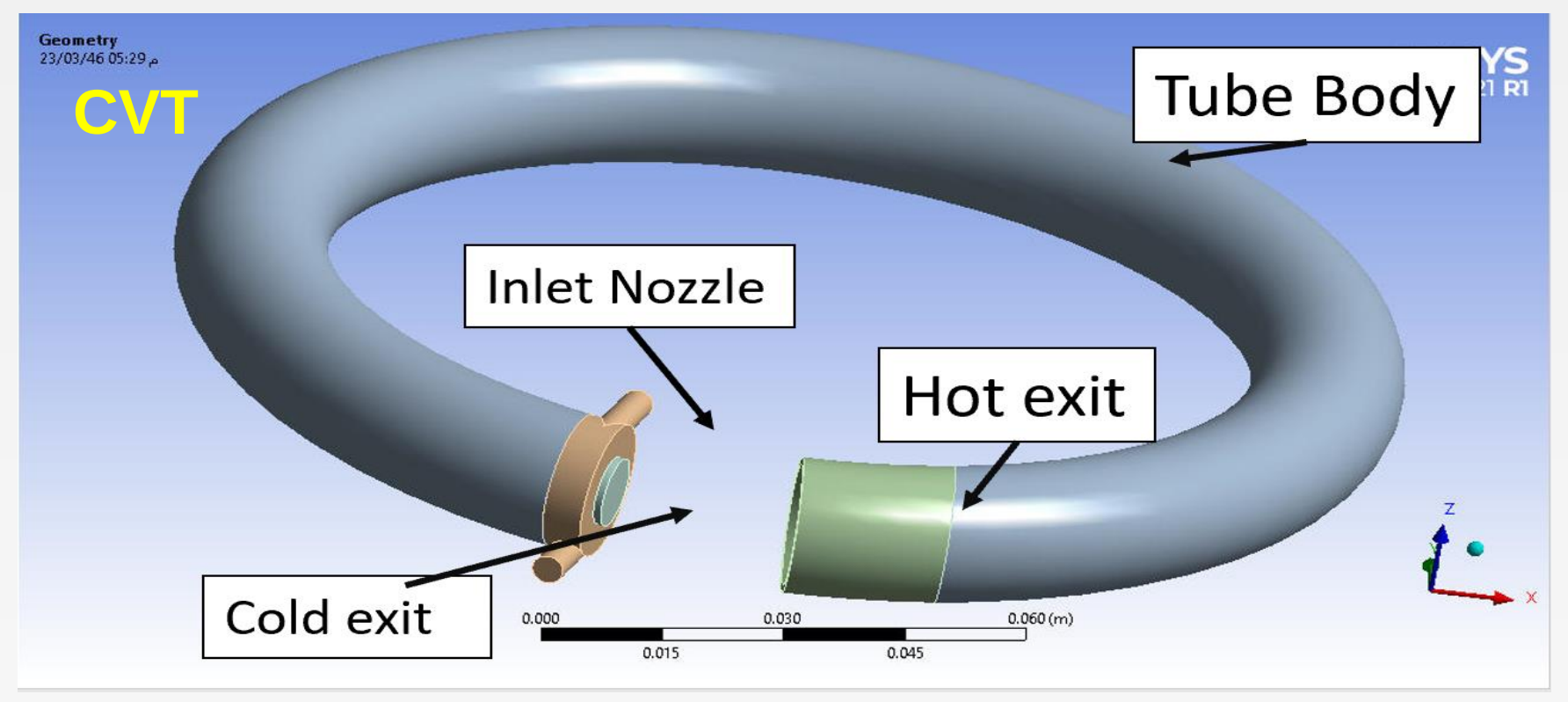
Geometry specification of SVT

Parameter	Dimension
Working tube length (L)	400 mm
Inner tube diameter (D)	19.05 mm
Cold exit diameter (d_c)	9.53 mm
Inner Nozzle diameter (d_n)	4.00 mm
Nozzle height	13.37 mm
Mean hot exit diameter (d_h)	18.025 mm
Hot exit area (A_h)	58.17 mm^2
Nozzle total inlet area (A_n)	25.13 mm^2



Geometry specification of CVT

Angle (degrees)	Radius (mm)	Length (mm)
110	208.34	167.22
150	152.78	228.03
180	127.32	273.63
270	84.88	410.45
310	73.93	471.26
340	67.4	516.86

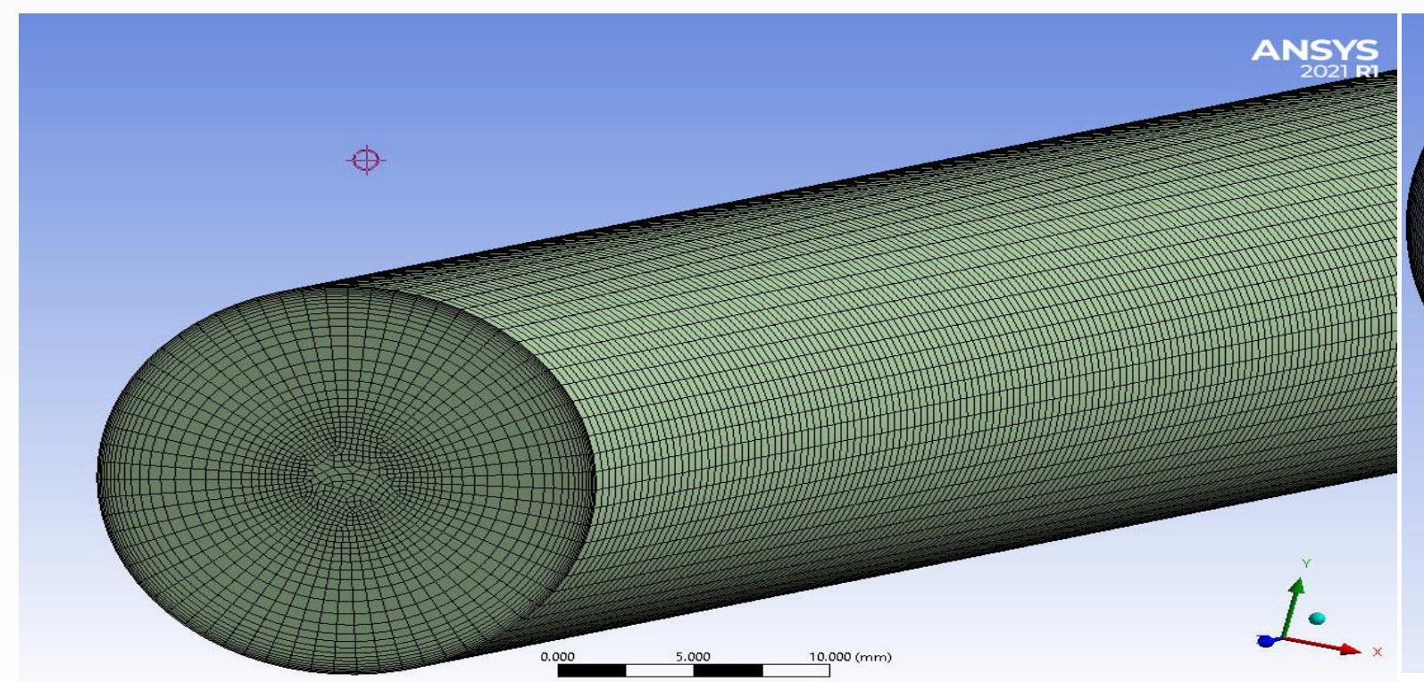


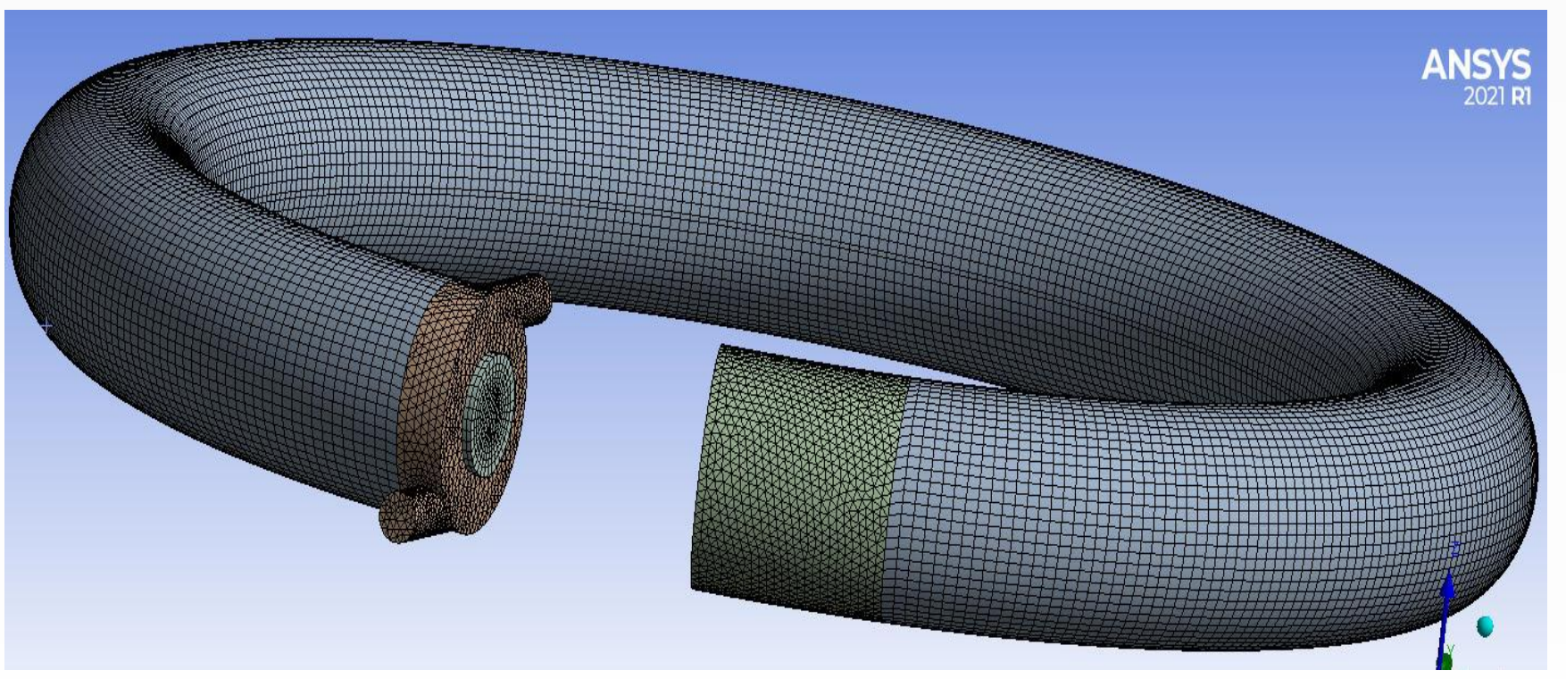
Discretization of models

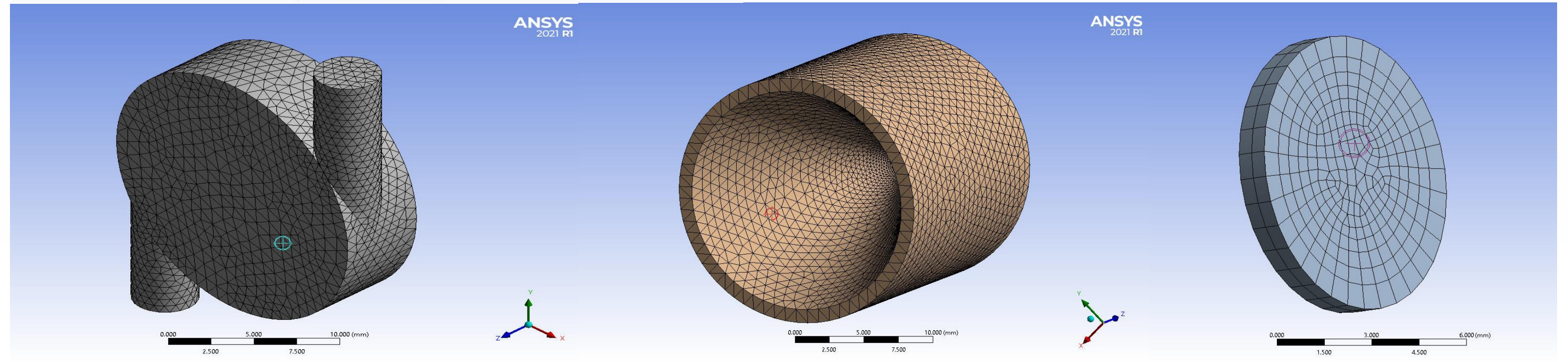
- Non-structured mesh was built to reduce total number of elements
- First step: Sweep meshing for tube body
- Second step: Apply inflation to enhance mesh density
- Third step: Tetrahedral mesh on remaining sections

Boundary conditions

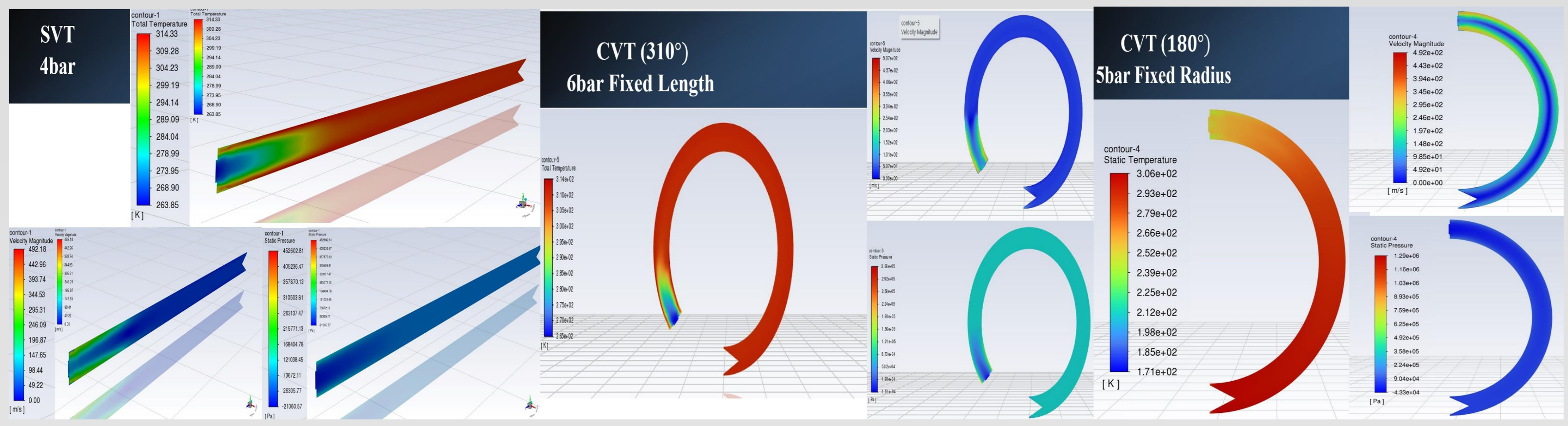
Boundary Type	Boundary Conditions	Value
Inlet	Pressure inlet	2-6 bar (total)
Cold exit	Pressure outlet	1 bar (static)
Hot exit	Pressure outlet	1.19 bar (static)
Operating pressure		0 [bar]
Walls	Adiabatic with no-slip	Heat flux = 0 $W\ m^{-2}$

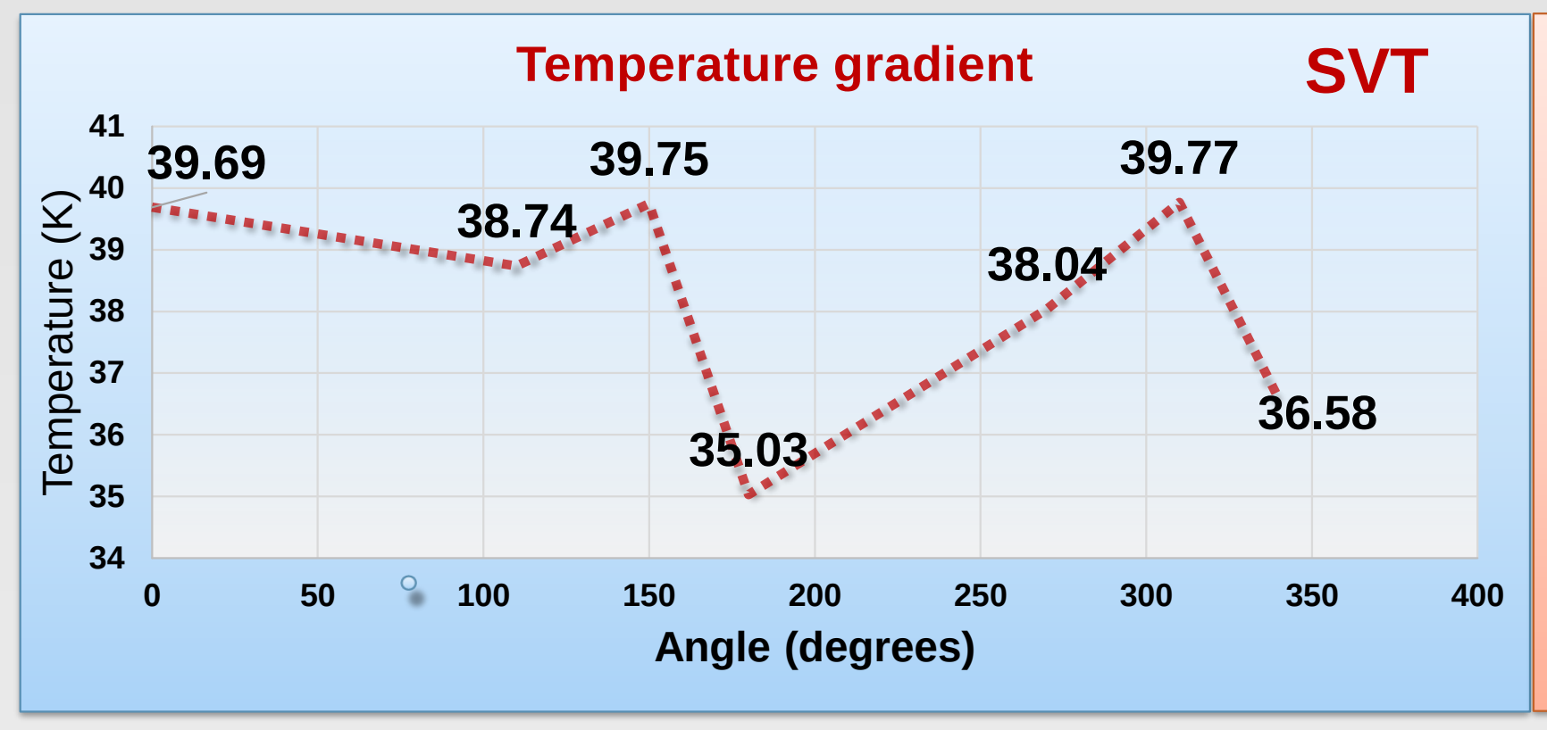


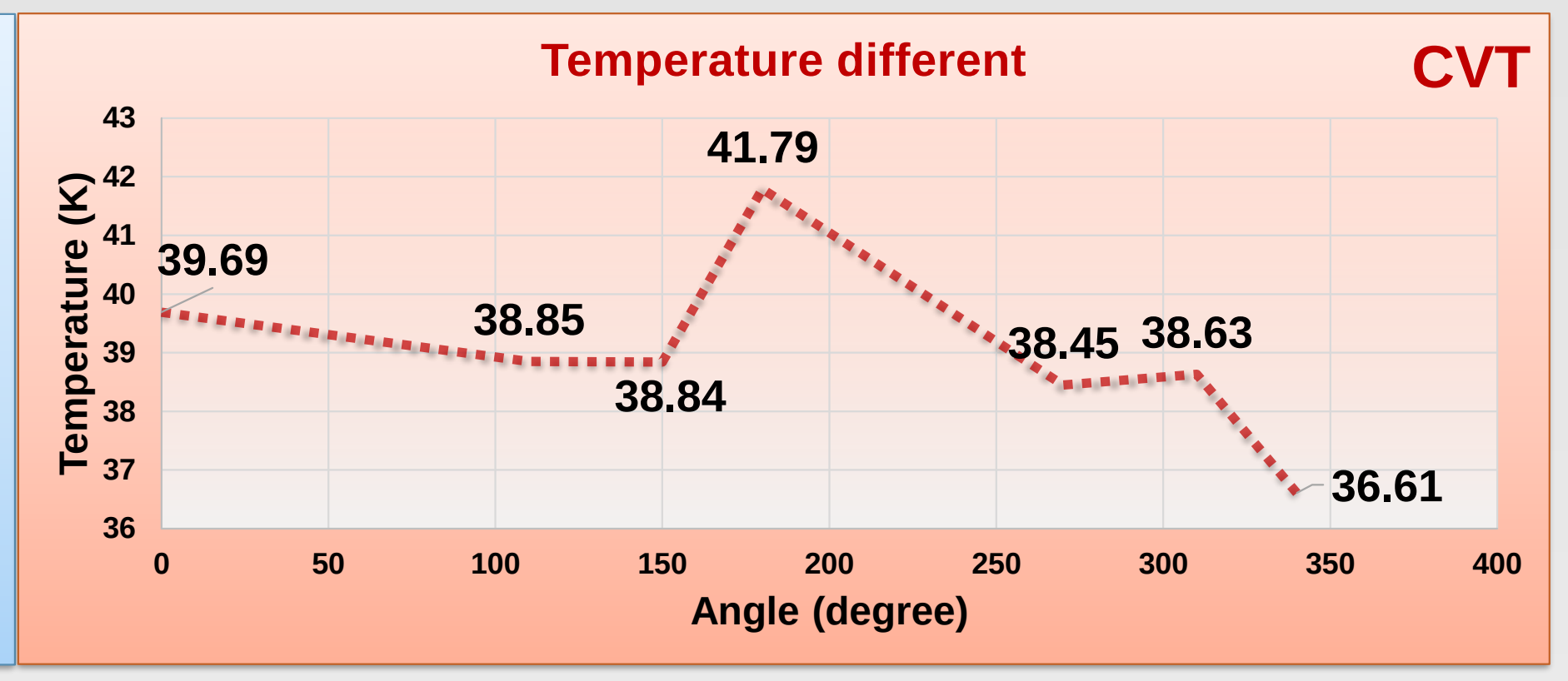




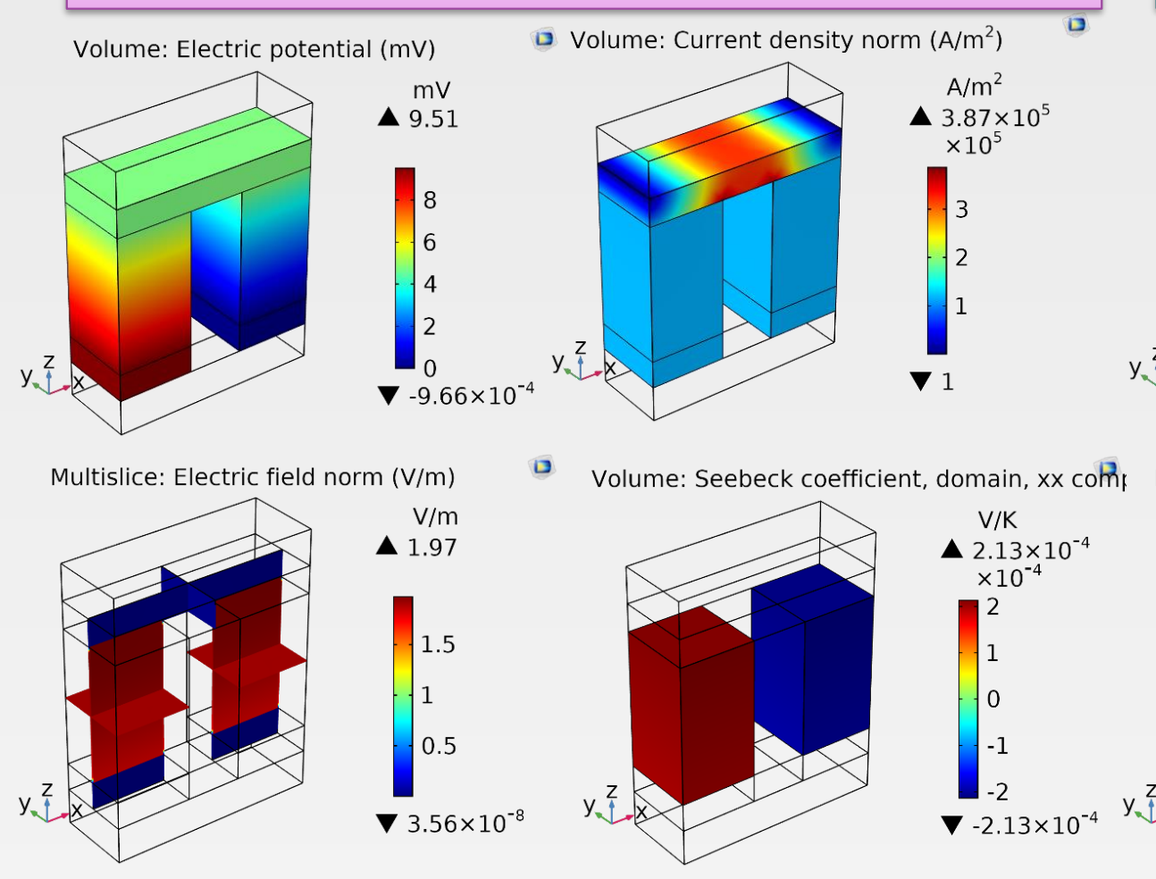
FINITE ELEMENT SIMULATIONS



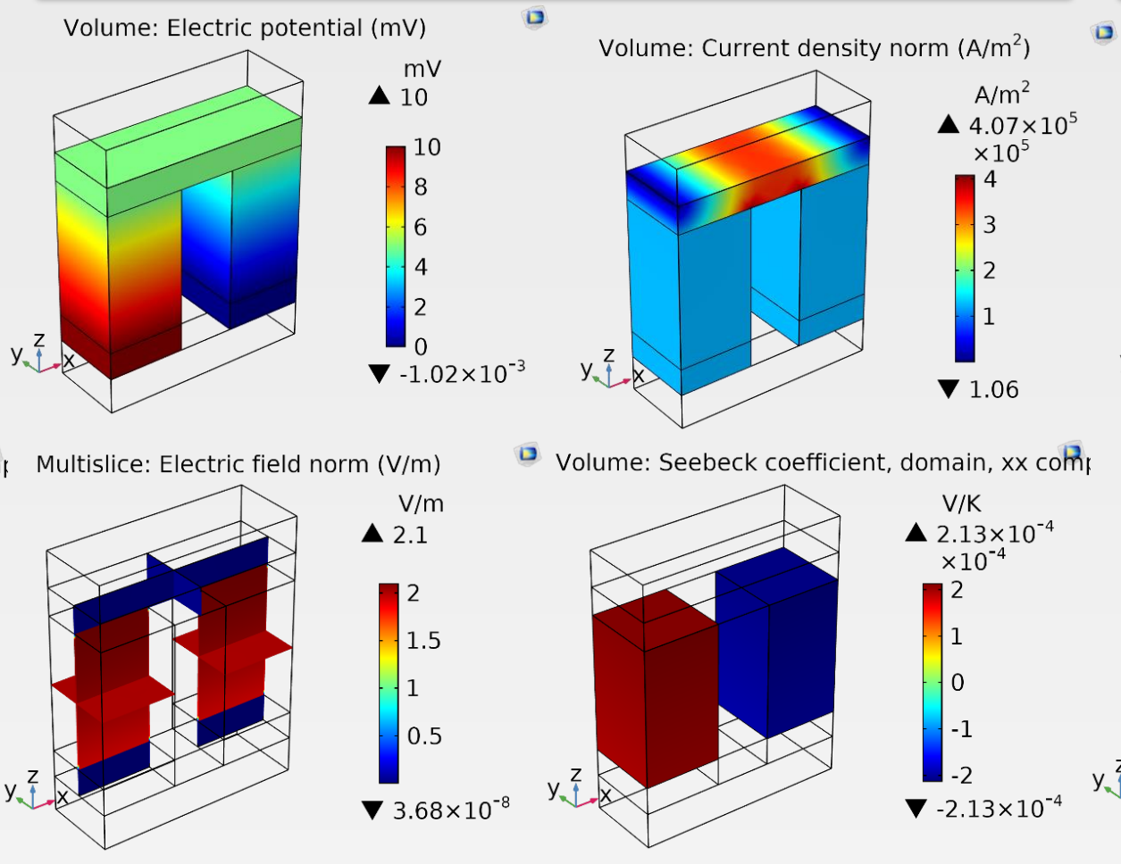




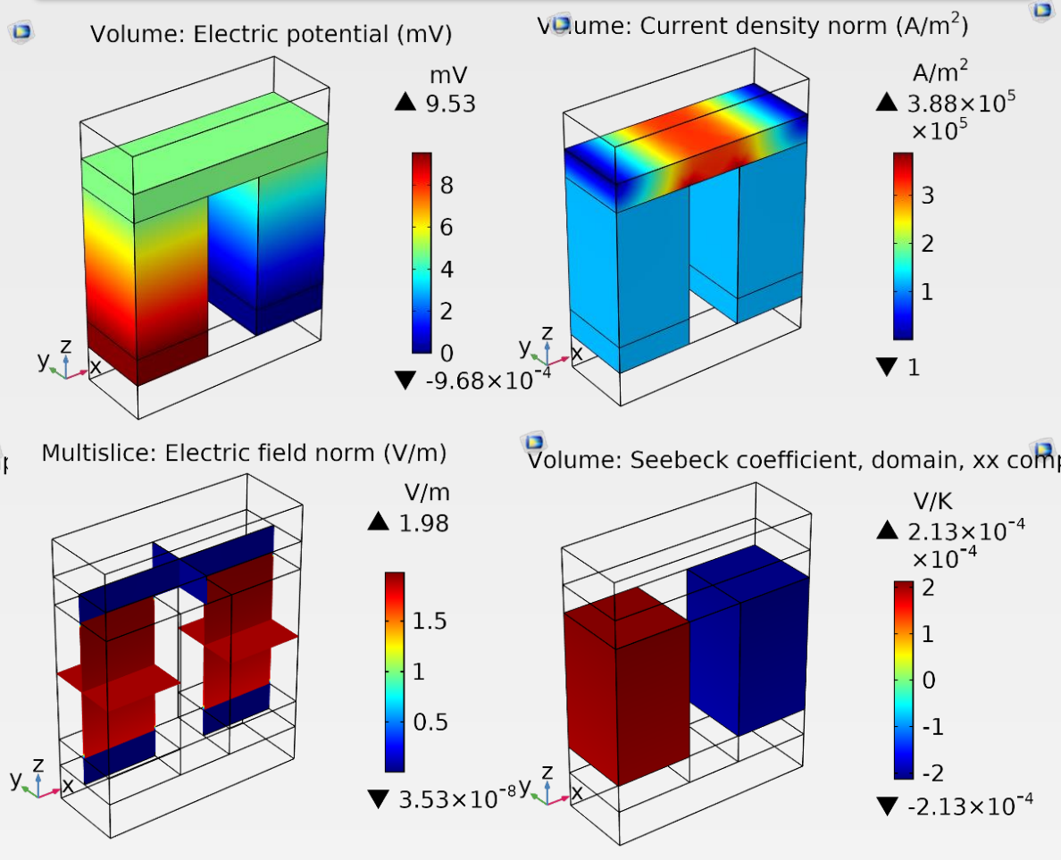
TeG-SVT Simulations



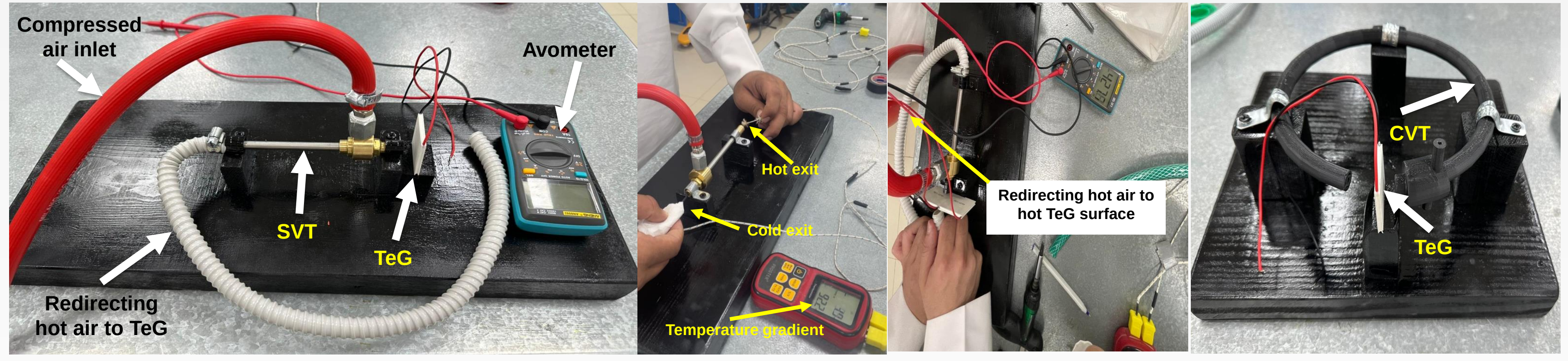
TeG-CVT (180°) Simulations



TeG-CVT (310°) Simulations



EXPERIMENTAL SETUP



It is observed experimentally in SVT that maximum ***temperature difference, 96.10 °C and voltage, 520.40 mA*** are at 6 bar inlet pressure

CONCLUSIONS

- ✓ SVT simulations show that 4 bar inlet pressure is optimum, $\Delta T = 39.69$ °C
- ✓ CVT simulations show that 6 bar at 310° is the optimum, $\Delta T = 39.77$ °C (fixed length), and 5 bar 180°, $\Delta T = 41.79$ °C. (fixed radius)
- ✓ Simulation results are not far from experimental observations for multi TeG system, however; require tunning to reduce error

REFERENCES

[1] S. Y. Khan, U. Allauddin, S. M. F. Hasani, R. Khan, and M. Arsalan, "A CFD analysis on the effect of tube curvature, hot flow control valve profile, and inlet swirl on the thermal performance of curved vortex tubes,"

[2] C. D. Fulton, "Ranque's tube," J. Am. Soc. Refrig. Eng., vol. 58, pp. 473–479, 1950.