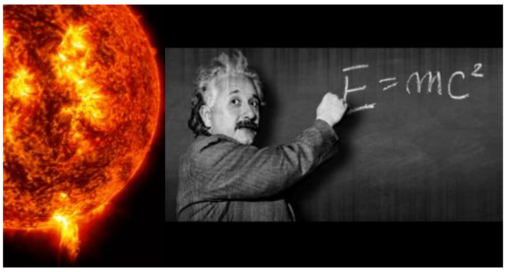
Towards Cooling of Future Nuclear Fusion Reactors: Numerical Study of the Cooling Characteristics of Supercritical CO_2 Flow through Metallic Channels

Background



In the core of the Sun, hydrogen atoms undergo high-speed collisions, leading to fusion and the formation of helium atoms. The mass of fused helium atom is slightly less than the combined mass of the hydrogen atoms, with the difference converted into a significant amount of energy. This is the phenomenon what the famous Einstein's equation $E=mc^2$ describes: a small loss of mass multiplied by the square of the speed of light results in a vast release of energy.

Here on Earth, efforts are directed towards achieving controlled fusion reactions using two isotopes of hydrogen - deuterium ($^2_1\mathrm{D}$) and tritium ($^3_1\mathrm{T}$). When these isotopes fuse, they produce an alpha particle ($^4_2\mathrm{He}$), a neutron ($^1_0\mathrm{n}$), and a significant amount of energy (17.6 MeV). This energy release is several orders of magnitude greater than that generated in chemical reactions involving fossil fuels.

$$^2_1\mathrm{D} + {}^3_1\mathrm{T} \rightarrow {}^4_2\mathrm{He} + {}^1_0\mathrm{n} + 17.6\ \mathrm{MeV}$$

One of the leading candidates for a fusion reactor to carry out the above reaction is called Tokamak, a toroidal (donut-shaped) device designed to confine hot plasma using magnetic fields, creating conditions favorable to the fusion of light elements and subsequent energy production (Figure 1). Within the tokamak, approximately 80% of the released fusion energy is transported by neutrons, which are absorbed by the reactor walls, converting their kinetic energy into heat.

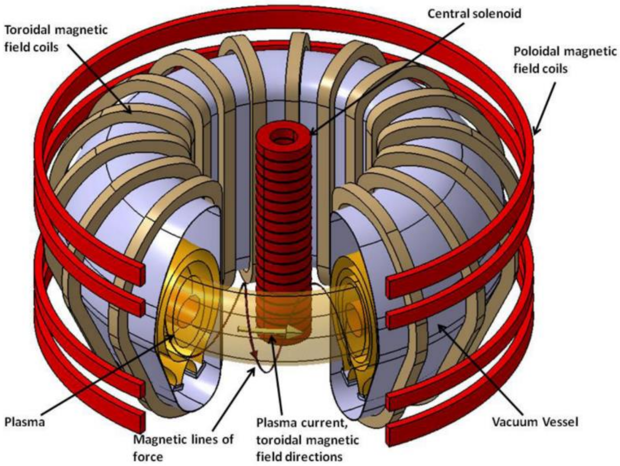


Figure 1: Schematic of a tokamak fusion reactor

Challenge

One of the primary challenges in reactor design concerns heat management. A critical component, known as the divertor (Figure 2 a), is employed to extract heat from the plasma and shield the reactor walls from damage. The substantial heat flux on this component (10-20 MW/m^2) poses significant engineering hurdles. Ongoing research and development efforts are focused on advancing high-heat-flux technologies and optimizing heat exhaust strategies for future reactors.

Currently, divertor technology utilizes tungsten mono-blocks housing CuCrZr cooling pipes circulating water as a coolant (Figure 2 b). In future fusion reactors anticipated to face even higher heat loads, the mono-block design may potentially be supplanted by Liquid-Metal Divertor (LMD) technology (Figure 2 c). LMD employs a porous front plate filled with liquid lithium, cooled by a coolant flowing through underlying tubes. Due to safety concerns regarding the interaction of water with liquid metal, helium gas and supercritical CO_2 are being considered as alternatives. However, the cooling performance of these fluids for fusion reactor applications has not been extensively studied. Therefore, there is a pressing need for systematic research to gain a comprehensive understanding of the cooling capabilities of each fluid.

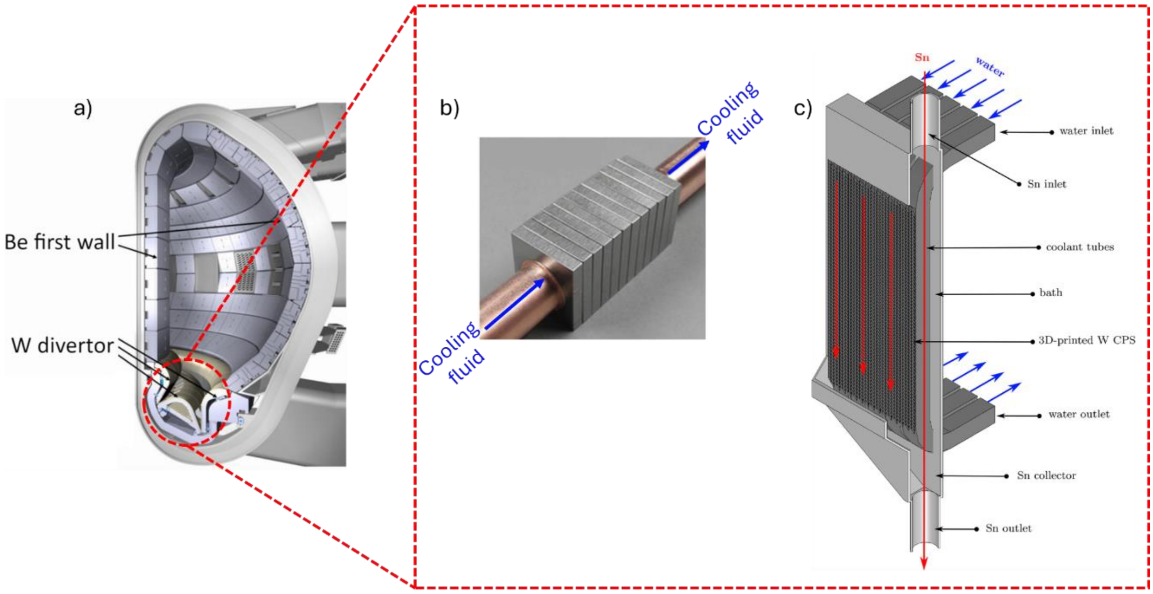


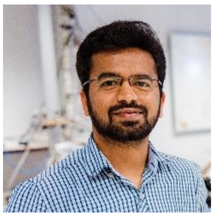
Figure 2: a) Cross-section of tokomak reactor with beryllium (Be) walls and tungsten (W) divertor that face the hot plasma; b) Tungsten mono-block design; c) Liquid-Metal Divertor technology

Objective

The objective of this assignment is to conduct a theoretical investigation into the cooling characteristics of supercritical CO_2 in a simplified geometry using analytical and/or computational tools. The scope of this assignment includes the following anticipated activities:

- Getting familiar with the supercritical state of CO_2 and developing an understanding of its properties.
- Modeling a conjugate heat transfer problem involving the flow of supercritical CO_2 within a tungsten mono-block.
- Expanding the model to the Liquid-Metal Divertor (LMD) technology by incorporating the evaporative flux of liquid metal.
- Comparing the cooling performance of supercritical CO_2 with that of helium gas and water, and providing recommendations for future fusion engineers regarding the selection of an appropriate cooling fluid.

Contact



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