Cryogenic Viscous Compressor Development and Modeling for the ITER Vacuum System


Oak Ridge National Laboratory
*ITER Organization

Presentation for:
64th IUVSTA Workshop
Summary

- ITER has unique vacuum pumping requirements due to high throughput tritium operation.

- The roughing system cannot utilize conventional pumps; therefore a cryopump (CVC) is being developed to effectively compress the DT + He gas mixture for pumping by T compatible backing pumps.

- A unique feature of the CVC is the ability to pump the hydrogenic species, while allowing helium impurities to be exhausted to atmosphere.

- The design is being modeled with a CFD code, which has helped to refine the design and is being used to compare with experiments.

- Modeling of a full scale prototype is underway that will be used to improve the final design.
ITER – Worlds Largest Fusion Experimental Reactor

ITER Highlights

- ~1300 m³ vacuum vessel volume, neutral beam, cryostat and service vacuum system.
- 8 Torus Cryopumps backed by large roughing pump system (C. Day, IAEA 2004, D. Murdoch IVC2007, …)
- Plasma contains ~2 bar-L equivalent gas
- Tritium compatibility of all systems from day one
- Operational 2019
Simplified ITER Fuel Cycle Flow Diagram

- Pellet Injector
- Cryo-Viscous Compressor
- Tritium Plant
- He
- DT

HHIM 2010
Why a Cryogenic Viscous Compressor?

- Output pressure from the torus cryopumps when they regenerate is ~ 500 Pa (5 mbar).

- Conventional vacuum pumps that operate at this pressure range (roots blowers, claw pumps, screw pumps) are not tritium compatible. (Oil, elastomer seals, and purge gas not allowed)

- A cryopump is tritium compatible and can regenerate to a high pressure (~10000 Pa) that scroll or piston pumps can pump. Thus the use of “compressor” in the name.

- A unique feature of the CVC is the ability to pump the hydrogenic species, using viscous drag to pull helium impurities through where they are exhausted to atmosphere by conventional pumps.
Inlet: ID 250mm, P = 100 Pa
Flow of up to 200 Pa·m³/s
DT + < 5% He gas mixture at 293 K

Chevron baffle for pre-cooling:
0.4 m high ID: 500 mm
To cool the gas to about 80 K

Condenser cooled with ScHe
Inlet: ~4.7 K outlet up to 80 K
24 pipes ID: 50 mm 1 m long

After the condenser tubes the Helium gas is separated from the DT gas and shall be pumped continuously by a backing system to DS
CVC Inlet Conditions and Flow Regime

• Inlet pressure to the pump is maintained $\leq 100$ Pa, with a maximum flow rate of $200 \text{ Pa-m}^3/\text{s}$.

• Reynolds number is low ($< 100$) thus the flow is very laminar and leads to poor heat transfer.

• Knudsen number at inlet is $\sim 0.01$ and Graetz number (dimensionless number characterizing laminar flow in a conduit) is quite low indicating fully thermally developed flow.

• The Nusselt number (ratio of convective to conductive heat transfer) is $<< 10$ and needs to be increased, therefore a swirl tape is considered.
Heat Transfer in Laminar Flow Circular Tubes

Fig. 3 Comparison of heat transfer correlations for laminar flow in circular tubes with a twisted-tape insert \((y = 2.5, \delta/d = 0.05)\) and uniform wall temperature

Methods to Improve the Heat Transfer in the CVC

Swirl Tape

Petal tube insert
Comparison of Temperatures and Flow Velocities Between Bare and Petal Insert Tubes in the CVC

Temperature and velocity are greatly affected by the petal insert in the CVC pump tubes as shown in this fluid dynamics modeling with the CFX code. This insert will improve the pumping effectiveness of the CVC.

Hydrogenic gas flow
H$_2$ Temperature and Density along the axis

**Temperature at the center of the tube**

**Density at the center of the tube**
**H₂ Velocity and Mean Free Path Along the Axis**

**Vertical Velocity of H₂ Gas**

- Reynolds number is ~100 indicating extremely laminar flow.

**Mean Free Path of H₂ Gas**

- Knudsen numbers in the range of .01-.002, factor of 2 lower with the petals.
Temperature Profiles

dashed line = with petals
continuous line = w/o petals
Modeling of Desublimation

- For the system defined by the pump surface, the energy transfer to the pump surface is energy transferred from the gas, plus the adsorption heat.

- Hydrogen isotopes chemisorb on the surface to form the first layer. Additional layers are formed by physisorption.

- Those two kinds of adsorption processes determine different adsorption heating. By calculating the surface time from adsorption heat, we conclude that the hydrogen isotopes stay in adsorbed layers once hitting the surface, while helium only quickly exchanges energy with surface.

- Self heating from tritium is estimated to be a total of < 5W

- Clearly CFD cannot model this section of the pump with rarefied gas and so alternative methods are being explored...advice is welcome.
Summary

- ITER has unique vacuum pumping requirements due to high throughput tritium operation.
- The roughing system cannot utilize conventional pumps; therefore a cryopump is being developed to effectively compress the DT + He gas mixture for pumping by T compatible backing pumps.
- A unique feature of the CVC is the ability to pump the hydrogenic species, while allowing helium impurities to be exhausted to atmosphere.
- The design is being modeled with a CFD code, which has helped to refine the design and is being used to compare with experiments.
- Modeling of a full scale prototype is underway that will be used to improve the final design.