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Research paper

Solid deposition in the ITER cryogenic viscous compressor

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ABSTRACT

A transient model for the ITER cryogenic viscous compressor (CVC) is presented. The CVC is designed to separate hydrogen isotopes from helium in the gas-mixture exhaust from the ITER torus. During their residence in the CVC, hydrogen isotopes are captured along the pump wall while helium flows through. The CVC thereby provides the first stage of helium compression. The transient model characterizes the transport phenomena (species, momentum, and energy) that occur in the CVC. The numerical results are compared with experimental data from a scaled down test of the ITER CVC using pure hydrogen. Although the model has been developed for a hydrogen–helium mixture, it is simplified here in order to compare with the experimental data. The transient model, along with other numerical models we have developed, provide guidance for the design and optimization of the ITER CVC. The model can also be a useful tool or a reference for similar analyses, such as those for cryogenic carbon capture and air ingress in vacuum isolated cryogenic vessels.

1. Introduction: the ITER cryogenic viscous compressor

Due to its enormous size and complexity, ITER presents numerous challenges for handling the flow of gases both into and out of the toroid-al plasma region that represents the heart of its operation. A recent and thorough description of the various vacuum systems associated with these flows is provided by Pearce et al. [1]. As described therein, six "Torus Cryogenic Pumps" (TCP) are sequentially utilized to evacuate the neutralized gas and helium that are produced by the operating fusion tokamak. The molecules that leave the plasma are pumped in the TCPs by adsorption onto activated charcoal at 4.5 K. Of the six TCPs included in the ITER design, only four of them are operating at any given time, while the other two undergo a regeneration procedure. During the regeneration process, a roughing pump system removes the released gases, including hydrogen isotopes, trace amounts of helium, and plasma enhancement gases such as neon or nitrogen, from the TCPs.

The cryogenic viscous compressor (CVC) along with mechanical pumps, make up the roughing system used to pump the fusion exhaust gas during the regenerating process of the TCPs [1–3]. The CVCs represent the first stage of the roughing pump system. They are designed to capture the hydrogen isotopes for subsequent reprocessing while allowing the trace helium to pass through. The CVC's unique working conditions present a number of significant modeling challenges. For example, the CVC behaves as a heat exchanger between the relatively warm low-pressure flow stream of the fusion exhaust gas, and the supercritical helium coolant. Condensation of the exhaust gas components at the CVC wall, or evaporation of the same components from the CVC wall, depends on the difference in pressure between the bulk gas flow and the saturation pressure associated with the wall temperature of the CVC. An energy balance at the wall that includes factors such as enthalpy in turn determines the wall temperature profile and phase change energies of the captured gas, heat transfer to the coolant, and a thermal resistance that depends on the thickness of mass deposited on the wall. Because of the interdependence of all these various factors, the operation of the CVC is very much a dynamic system.

In view of the complex nature of the CVC, both experimental and theoretical investigations have been carried out in order to characterize its operation and provide appropriate design guidelines. Oak Ridge National Lab has built and tested a scaled down model of the CVC [4–6], while efforts at the University of Wisconsin-Madison [7] have focused on the physical analysis and modeling. The results of the model display that the combination of conservation equations for mass (species), momentum, and energy allow one to determine the rate and location of mass deposition on the walls of the scaled-down CVC, as well as the temperature and pressure profiles through its length.

The following sections will briefly review the experimental subscale CVC test at ORNL and subsequently describe in detail the

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development and results of an associated numerical model at UW-Madison. The experimental data provide a reference for the theoretical models, and the theoretical work can provide guidance for any future experiments and the operation of the full scale CVC.

2. Sub-scale CVC test at ORNL

The scaled down version of the ITER cryogenic viscous compressor being tested at Oak Ridge National Lab exists as a concentric tube-in-tube heat exchanger, spanning a length of about 1.07 m, with an inner diameter of 5 cm, and an overall outer diameter of 15.24 cm. Pure hydrogen gas, or a mixture of hydrogen isotopes and with trace amounts of helium gas (about 1%), flows through the inner tube while cold helium gas (7–9 K) flows as a coolant through the outer annular tube.

Fig. 1a shows the experiment setup, including the concentric tube-in-tube heat exchanger, mass flow controllers, instrumentation, and roughing pump. As shown in Fig. 1b, four silicon diode type thermometers, with a typical accuracy of less than ±30 mK are mounted on the outer surface of the cryopump tube to measure the tube wall temperature. To avoid communication with the helium coolant flow stream, some insulation surrounds the temperature sensors. As measured from the hydrogen flow entrance (left) end, the first thermometer (measuring $T_{wall,4}$) is located 10.2 cm axially along the tube. The three subsequent thermometers are mounted 30.5 cm apart along the tube, and they measure $T_{wall,3}$, $T_{wall,2}$, and $T_{wall,1}$ respectively. Two silicon diode type thermometers are used to measure the inlet and outlet temperatures of the helium coolant. The thermometer measuring the helium coolant inlet temperature is mounted on a Teflon screw secured to a baffle and located about 7.5 cm axially beyond the $T_{wall,1}$ thermometer (106.7 cm from the left end) and radially about 5 cm inside the outer wall. The thermometer measuring the helium coolant outlet temperature is mounted on a Teflon rod about 10.2 cm from the left end of the tube and secured with Teflon nuts approximately 2.5 cm radially inside the outer tube wall.

Two pressure gauges (MKS model 722B with accuracy of 0.5% of reading) are used to measure the upstream and downstream pressure of the hydrogen flow, and these provide absolute pressure measurements. The upstream pressure gauge is connected with a capillary tube to a location 7 cm from the left end of the tube, while the downstream pressure gauge is mounted on the exit of the entire setup. An axial distance of approximately 2.16 m separates the two pressure transducers. Note that the inner concentric tube extends beyond the co-axial section of the CVC tube in which region it has an inner diameter of approximately 5 cm. The downstream pressure gauge is located at the outlet of this extended section. Additional pressure gauges are used to measure the pressure of the hydrogen gas supply and the ballast tank. The gauge for the hydrogen gas supply is mounted downstream of the flow controllers but upstream of the precooler.

Model 1480A MKS Instruments flow controllers are used as mass controllers. For hydrogen flow, the controller is a 0–10,000 sccm controller, while for helium flow, the controller is a 0–1000 sccm controller. Each of the controllers is calibrated for their respective gas. The controllers utilize a 0–5 V control signal and the control signal is adjusted to set the incoming flow rates.

The u-tube at the far-right end of the test rig has an outer diameter of 5.08 cm with a wall thickness of 0.9 mm. Each leg of the u-tube is nominally 10 cm long and the connecting piece is approximately 15 cm long. The buffer volume of the ballast tank is approximately 30 in. long with a 40.6 cm diameter.

A helium coolant flow rate of about 0.5 g/s is associated with a velocity of about 3 mm/s. If the tube length is divided into 50 nodes, the time for the helium coolant to travel from one node to its adjacent neighbor is about 8 s.

A hydrogen gas flow rate of about 0.001 g/s, is associated with an inlet velocity of about 4 m/s. The velocity decreases quickly as the gas is cooled.

It is helpful to note a variety of relevant time constants and length scales associated with the sub-scale CVC test rig: For the inlet condition of hydrogen flow at 80 K and 100 Pa, the speed of sound is 733.1 m/s and it thus takes about 0.001 s for a (viscous) pressure signal to travel the length of the 1 m cryogenic viscous compressor. The mass diffusion coefficient is about 0.01335 m^2/s, and it thus takes about 0.01 s for molecules to diffuse from the centerline to the surface of a tube with a 5 cm diameter.

At 80 K, the thermal velocity of hydrogen molecules is about 916.6 m/s. At this temperature and for pressures less than 6 Pa, hydrogen is rarefied and the molecules traveling at their thermal velocity will take about 0.0005 s to form 5 adsorption layers on the surface of the cryogenic pump. At 10 K, the transition from viscous to rarefied conditions occurs as the pressure falls below 0.7 Pa.

At 80 K and 100 Pa, the mean free path of hydrogen and helium are about 0.0329 mm and 0.0523 mm respectively. Both are much smaller than the 50 mm pump diameter. When the gas temperature and pressure approaches 10 K and 0.7 Pa, the mean free path becomes comparable to 0.01 times the pump diameter, the condition at which the transition from viscous to molecular flow begins. Note that the saturation temperature and associated saturation pressure at which the mean free path of hydrogen equals 0.01 times the pump diameter is 6.155 K and 0.458 Pa.

The diffusion coefficient for hydrogen gas ranges between 0.0004 m^2/s and 0.03 m^2/s, and depends significantly on temperature.

3. Analysis and governing equations

3.1. Molecular and viscous flow regimes

Typically, cryopumps are used to create or maintain a relatively high vacuum [8,9], and usually operate in the rarefied gas regime. Molecules are ‘pumped’ when they are trapped on solid surfaces at cryogenic temperatures. The pumping process results from a physical adsorption mechanism that depends on factors such as surface condition and molecule species. As a result, a Monte Carlo method [10–12] is usually applied to model the physical processes operative in a cryopump.

In contrast with common cryogenic pumps, the nature of the ITER CVC is the cryogenic deposition of the hydrogen molecules from a viscous gas flow into the liquid or solid form on the pump surface. The crucial point is that the CVC works in the viscous flow regime. In fact, even if at the inlet temperature of 80 K, the total inlet gas pressure is as low as 6 Pa, the gas remains in the viscous, rather than the molecular flow regime. The incoming hydrogen molecules collide with other molecules more frequently than with the pump surface, and they behave as a bulk gas flow. Additionally the ITER CVC processes many more molecules than those being processed by a common cryogenic pump.

As a result, neither chemical adsorption nor physical adsorption is the major mechanism for cryogenic pumping in the ITER CVC. It is possible though that the gas-surface interaction is important at the very beginning of the cryogenic pumping process if the pump surface is initially clean and free of contamination. The available sites for physical adsorption are too few compared to the large amount of hydrogen molecules entering the pump. The process of the gas-surface interaction is very short and unimportant in the entire cryogenic pumping process. The available sites are soon occupied, and the surface of the ITER CVC is quickly covered by the hydrogen molecules.