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Evaluation of Supercritical Helium as a Coolant for DIII–D-Type Cryocondensation Pumps

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Abstract. The DIII–D tokamak uses three cryocondensation pumps for plasma density control. Each DIII–D pump consists of a series of concentric stainless steel tubes assembled together. The pumping surface is a 25 mm diameter stainless steel tube. The pumping surface of each of the three cryocondensation pumps is about 1 m^2 in area and is maintained below 5 K by cooling two phase helium (1.3 atm, 4.35 K). The two phase helium (TP) was chosen for DIII–D because it is available at the DIII–D site and is used for neutral beam (NB) and other applications. The pumping speed is about 30000 ℓ/s per pump. The three pumps inside DIII–D have performed as expected for the last several years.

Superconducting machines under construction, such as KSTAR and SST-1 have supercritical (SC) helium available on site. The device operator would prefer to use it for cooling the cryocondensation pumps. The typical condition of the available helium is 0.4 MPa (3.94 atm) pressure and 4.2 K temperature.

The design of the DIII–D cryocondensation pump is simple, robust, inexpensive and reliable. This study was undertaken to evaluate if the supercritical helium can be used as a coolant for the GA design of the cryocondensation pump. It is concluded that with supercritical helium a flow rate of 50 to 60 gm/s (compared to 5 to 10 gm/s with two phase helium) will be required to achieve a similar performance. The co-axial insert used in DIII–D helium panel will not be required with SC helium.

I. INTRODUCTION

Presently three cryocondensation pumps are used in the DIII–D tokamak. These are simple in construction and have operated reliably for the last several years. A two phase (TP) helium flow is used as a coolant for the cryocondensation surfaces of these pumps. Several new machines under construction such as KSTAR and SST-1 also need cryocondensation pumps. These machines use superconducting magnets and use supercritical helium (SC) to cool the magnets. Hence, use of supercritical helium will be preferred for cryocondensation pumps in these machines. This study was undertaken to investigate how the DIII–D design of cryocondensation pumps will work if cooled by supercritical helium.

II. DIII-D CRYOCONDENSATION PUMP DESIGN AND PERFORMANCE

The geometry of the DIII–D cryocondensation pump is shown in Fig. 1. Each DIII–D pump consists of three of concentric stainless steel tubes, comprising the cryocondensation surface, a nitrogen shield and a particle shield [1]. The pump is a toroidally continuous structure to minimize electrical breakdown in low density plasmas. The condensation surface consists of a 25 mm stainless steel tube, cooled by two phase helium. The nitrogen shield is the main structural element and is 8 cm in diameter with cutouts for the pumping aperture. In order to increase the flow velocity, heat transfer coefficient and flow stability of the two phase helium flow, an annular insert of 19 mm diameter is used in the helium flow channel. Experiments show that the insert improves the performance of the pump significantly [2]. The chief characteristics of each of the DIII–D pumps are shown in Table I.

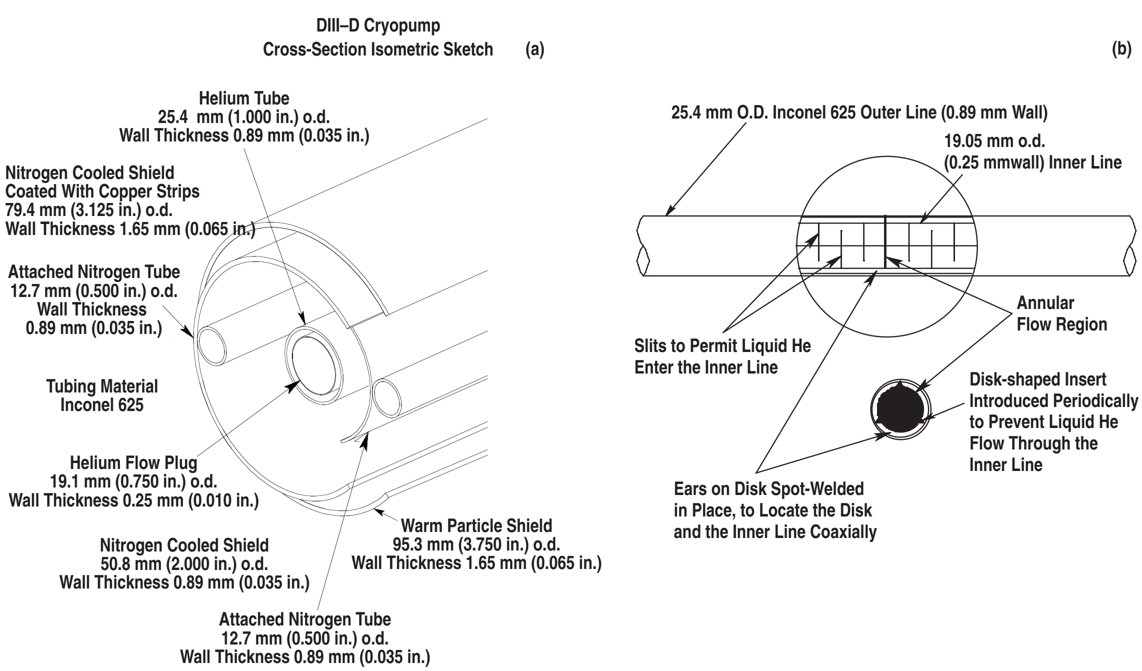

Fig. 1. Geometry of DIII–D cryocendensation pump.

TABLE I
CHARACTERISTICS OF THE DIII–D CRYOPUMPS

Pumping capacity of each	30,000 ℓ/s
Pulse length	5 to 10 s (maximum achieved 50 s)
Perimeter of the pump	8 to 10 m
Heat load	Conduction and radiation = 10 W continuous Joule = 30 W for 10 s Particle = 12 W for 10 s
External area	1 m^2
Helium coolant inlet condition	4.35 K, 1.3 bar
Flow rate	5 g/s

Experiments performed on a prototypical DIII–D pump with a flow rate of 5 g/s indicated a surface temperature of less than 5 K under heat load conditions [2] of 100 W for 30 s + 10 W for 40 s.

III. THERMODYNAMICS OF TWO PHASE HELIUM AND SUPERCRITICAL HELIUM

A temperature entropy diagram for helium is shown in Fig. 2. The critical pressure for helium, Pc, is 2.3 bar (33.2 psia). Helium above the supercritical pressure is called supercritical helium. If heat energy is added to the helium, as long as the pressure is above Pc, helium does not go through a phase change and consequently there is no latent heat of evaporation. There are several advantages of this behavior: 1) Heat transfer rates higher than for two phase helium can be obtained, at higher flow rates (discussed below). 2) Sudden decrease in heat transfer rate, such as boiling two phase helium at critical heat flux is very unlikely. 3) Flow instabilities are minimal to non-existent 4) Operating temperature can be optimized over a wider range and 5) Pressure drops are lower.

On the other hand, if the inlet pressure is below Pc, and the inlet fluid is a liquid, addition of heat results in evaporation of the liquid and results in two phase helium. There is very little change in temperature of the fluid until all the liquid is evaporated. However, there is a large change in the density of the two phase mixture because the density of the helium gas is three orders of magnitude less than the density of the liquid. The advantages of using two phase helium as a coolant are:

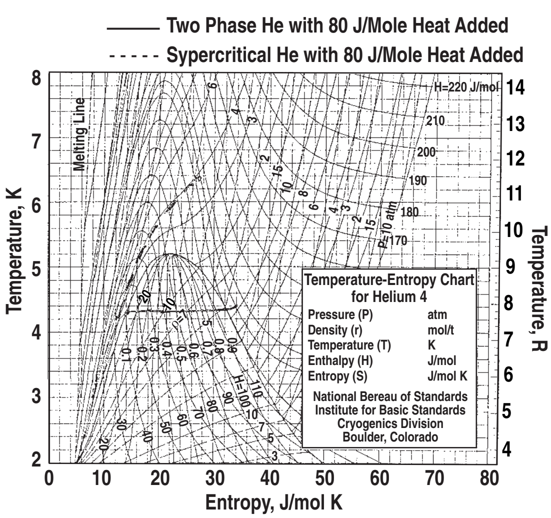

Fig. 2. T-s diagram for He.

1) Near isothermal conditions from inlet to outlet can be obtained. In fact, the outlet temperature can be slightly lower than the inlet temperature due to pressure drop and corresponding lower saturation temperature. 2) The flow rate required to remove the same heat load is smaller due to use of latent heat of evaporation.

IV. THERMAL HYDRAULIC EVALUATION

The maximum surface temperature, T_s, of the cryo-condensation pump for a heat load Q is:

$$T_s = T_i + \Delta T_B + \Delta T_f + \Delta T_s \quad , \qquad (1)$$

where:

T_i =	inlet temperature
ΔT_B =	change in coolant temperature from inlet to outlet
q'' =	heat flux = Q/A
A =	area of the pumping surface
ΔT_f =	film temperature drop = q''/h
h =	heat transfer coefficient
ΔT_s =	temperature drop in the wall of the pump (not a function of cooling method)

We will consider how the two quantities ΔT_B, ΔT_f are affected by the coolant condition.

A. *Change In Coolant Temperature*

The coolant temperature rise depends on the energy added to the coolant.

$$Q = m(h_2 - h_1) \quad , \qquad (2)$$

where:

h_1 and h_2 =	enthalpy of the fluid at inlet and outlet
m =	mass flow rate of helium

For a given mass flow rate, the increase in enthalpy for TP and SC helium will be same for the same heat load. However, the change in temperatures of the fluids from inlet to outlet could be quite different. If 20 J of energy (heat) is added to a gram of liquid helium (80 J/mol) at a temperature of 4.35 K and 0.132 MPa pressure, the change in temperature of the coolant is only 0.15 K (accounting for inlet to outlet pressure drop of 0.012 MPa). For a similar addition of energy to SC helium at an inlet temperature of 4.2 K and 0.4 MPa, the resulting temperature will be 6.35 K. This level of temperature increase is enormous for this cryocondensation pump applicationbecause the surface temperature has to be less than 5 K. To maintain the same exit temperature, a considerably larger flow rate will be required for SC helium compared to a TP helium.

The numbers are shown in Table II and the process is illustrated in Fig. 2.

In order to limit the exit temperature to 4.5 K, the flow rate for SC helium will have to be considerably larger.

B. *SC Helium*

The heat transfer for SC (single phase) helium in the range 4 to 20 K and 0.3 to 2 MPa (3 to 20 atm) can be predicted by [3]:

$$Nu = 0.0259(Re)^{0.8}(Pr)^{0.4}(Tw/Tb)^{-0.716} \quad , \qquad (3)$$

TABLE II
CHANGE IN COOLANT TEMPERATURES FOR TP AND SC HELIUM FOR 80 J/MOL ENTHALPY CASE

	In Pressure (MPa)	Initial T (K)	Inlet enthalpy (J/mol)	ΔH (J/mol) (change in enthalpy)	(J/mol)Exit Enthalpy	Exit T (K)	Exit Pressure (MPa)
Two Phase He	0.132	4.35	40.	80	120	4.5	0.12
Supercritical	0.4	4.2	35.	80	115	6.35	0.39

where:

Nu = Nusselt number
Re = Reynolds number
Pr = Prandtl number
Tw & Tb = wall temperature and Helium temperatures

C. Two Phase Helium

The calculation of the heat transfer coefficient in two phase helium is more complicated. It is function of quality of the flow, densities, and viscosities of liquid and vapor [4].

The heat transfer coefficient is:

$$Nu = 0.023(Re)^{0.8}(Pr)^{0.4}(5.4Xtt)^{-0.385} \quad , \qquad (4)$$

where:

x= quality of the fluid = mass of vapor/mass of liquid
Xtt = Martinelli - parameter = $\{(1-x)/x\}^{0.9}(\rho l/\rho g)^{-0.5}(\mu l/\mu g)^{0.1}$
Re = Reynolds number for liquid flow
Nu = Nusselt number
Pr = Prandtl number for liquid

Fig. 3 shows the relation between heat load on the pump and film drop for TP and SC helium. A larger flow rate is used for SC because (Section 6) it is required to limit the coolant temperature rise.

Thus, the film drop for TP helium and SC helium (at a higher flowrate) is quite small.

V. FLOW STABILITY

Two phase flow can lead to flow instabilities if the flow velocity is low and the quality of the flow (x = mass of vapor/mass of liquid) is high. Fig. 4 shows the Baker flow diagram for two phase flow regions [5]. It is desirable to operate in the bubble flow regime. If the flow is not bubble, the film temperature drop in the upper part of the cryo-condensation pump will be high (due to lower, gas-only heat transfer) making that part useless for cryopumping. Studies [5,6] have shown that the Baker diagram under-predicts the region of homogeneous flow by up to an order of magnitude for helium. Experiments at GA confirmed this behavior [2]. The stability of the two phase helium flow at a flow rate of 5 gm/s and heat loads up to 70 W of steady-state heat load (for 1 m^2 area) was improved for the GA design by adding an annular insert in the flow channel. This resulted in an increase in the flow velocity by a factor of about 3 for same flow rate. Fig. 4 shows how the stability of the GA cryopump for two phase flow was increased without increasing the flow rate due to the insert.

For SC helium there is no phase change and no concern about instability of this kind.

VI. FLOW RATES (FOR SAME SURFACE TEMPERATURE) AT SAME HEAT LOAD COMPARISON

If we need to operate the DIII–D pumps for a steady-state heat load of 100 W, a flow rate of 7 gm/s will be required for TP flow to insure stability and two phase flow at the exit. The surface temperature of the pump surface will be 4.71°C as shown in Table III.

For supercritical inlet flow, a larger a flow rate of 60 gm/s will be required to insure that the temperature rise of the coolant is limited. To achieve the same surface temperature, a flow rate of 60 gm/s will be required as shown in Table IV.

VII. DISCUSSION

A. KSTAR Requirements

During the initial phase, KSTAR [8] will be operated for a shorter pulse with only one NB. Upgrade is more ambitious. Estimates of pumping requirements are shown in Table IV.

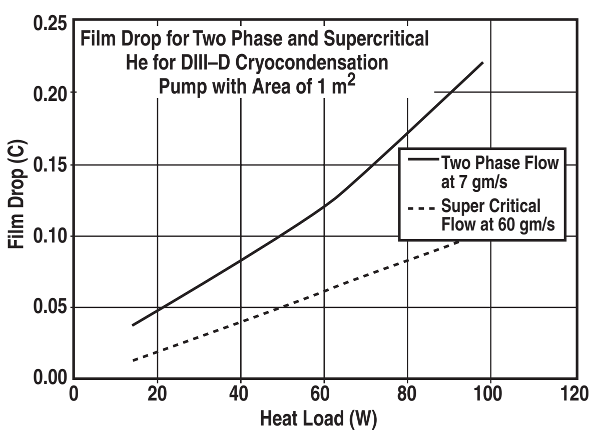

Fig. 3. Film drops for two phase and supercritical helium for DIII–D cryocondensation pump.

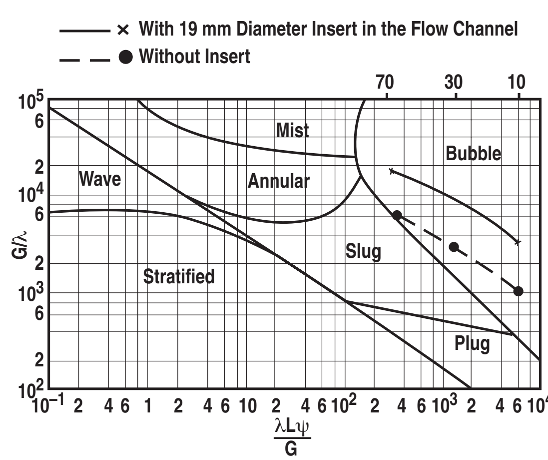

Fig. 4. Stability of two phase helium flow in DIII–D cryocondensation pump.

TABLE III
COMPARISON OF TWO PHASE AND SUPERCRITICAL HELIUM

	Inlet temperature	Outlet temperature	Film Drop	Drop through the tube thickness	Surface Temperature
7 gm/s of TP	4.35	4.6	0.2	0.01	4.71
60 gm/s of SC	4.2	4.6	0.1	0.01	4.71

TABLE IV
KSTAR REQUIREMENTS

	Initial	Upgrade
Pumping speed	50,000 ℓ/s	150,000 ℓ/s
Pulse length	20 s	300 s
Perimeter	12.5 m	12.5 m
Helium coolant	4.2 K, 3.9 atm	4.2 K, 3.9 atm

1. Assuming that conduction, radiation and particle heat loads are similar to the DIII–D design, a pumping speed of 50,000 ℓ/s for a pulse length 20 s (as required for the initial phase) is easily achievable with very little change in the DIII–D design by using one pump of DIII–D size. The surface area of the pump will be about 10 m^2. The flow rate required will be about 60 gm/s if SC helium is used.
2. There is no advantage in using the insert if SC helium is used.
3. For KSTAR upgrade, larger multiple pumps will be required.
4. DIII–D cryocondensation pumps can be cooled down from 300 K to 4.5 K in a few minutes. Use of SC helium at a higher flow rate will achieve the same result.
5. One of the large heat loads on DIII–D pumps is joule heating during current ramp-up. This occurs due to the toroidally continuous construction of the pump. Such a load will not occur in a superconducting machine.

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