Fundamental Analysis of Helium-Gas Coolant Leakage Rate Through First-Wall Cracks in Tokamak Fusion Reactors*

Tony C. Min

Department of Mechanical Engineering, North Carolina A & T State University, Greensboro, NC 27411, U.S.A.

A fundamental analysis of helium-gas coolant leakage rate through first-wall cracks in Tokamak fusion reactors was made. Criteria for ascertaining the correct flow models were thoroughly investigated. After testing the criteria, it was determined that the correct model is the compressible choked flow for the helium-gas coolant under the normal operating conditions in the Tokamak fusion reactors. The upper bound leakage rates through metallic wall for two crack sizes were calculated. The calculated maximum numbers of allowable cracks through metallic and silicon-carbon composite wall were also reported.

The experimental data of specimen S-23 (the small crack size), checked with the predicted or calculated leakage rate. But the experimental data of specimen S-4 (the large crack size, which is only 4.4 times larger than the crack size of specimen S-23) were two orders of magnitude higher than the calculated value. This is probably due to the many through-cracks undetected and therefore, not reported in the experiment, and not due to the difference in crack sizes. It should be noted that since there are only two test data points, it is recommended that more testing or experimental data will be needed.

The results of two previous investigations about the calculated leakage values, their equations used, and their flow models employed were also reviewed. It is concluded that the correct model for the analysis is the compressible choked flow, and that helium can be as an effective coolant for fusion power reactors. Several recommendations are also made. Specifically, more experiments for helium, and similar analysis and experiments for lithium and water coolant are needed; and should be encouraged.

Keywords: coolant leakage rate, Tokamak fusion reactor flow model.

INTRODUCTION

The lifetime of the fusion reactor first wall will depend upon many factors such as primary and cyclic structural loadings, material, temperature distribution, high neutron flux, plasma-wall interaction, and wall and coolant interaction. In this paper, we are basically concerned with primary blanket coolant leaks through assumed cracks or flaws in the first wall, as a fusion reactor vacuum first wall may lose its vacuum integrity. By allowing excessive coolant to leak into the plasma, this can quench the plasma burn of a fusion power reactor.

Specifically, we have investigated the theoretical helium-gas coolant leakage rates through given sizes of cracks of a stainless steel 316 metallic wall and a silicon carbide composite wall in some representative operating conditions for Tokamak fusion reactors. Rigorous criterion for determining correct gas flow models are first established, and then the theoretical leakage rates through cracks of metallic and ceramic composite wall are presented. Also the maximum number of allowable cracks through both types of wall are reported. Comparison with experimental data of two tests and theoretical values of other investigators are discussed.

GAS-FLOW MODELS

To estimate the potential leakage rate of coolant into the vacuum chamber of a fusion power reactor, it is extremely important that a correct flow model be selected before any calculations are made, otherwise the effort will be in vain and fruitless.
There are three possible models for gas-flow through a small crack, namely free molecular flow, incompressible flow, and compressible flow. They can be classified by pressure range, pressure ratio, and/or pressure difference.

In general, our intuitive rules of thumbs are as follows: a) If the gas pressure range is below atmospheric, the gas flow can usually be considered as molecular flow. b) If the gas pressure range is near or slightly above atmospheric, and the pressure drop is relatively small, the gas flow may be considered as incompressible. c) If the inlet gas pressure is above atmospheric and high, and the outlet to inlet pressure ratio is much less than unity, the flow may belong to the compressible type. However, we must quantify and be more specific about the rules in order to ascertain the suitable flow model.

Therefore in this study, we started by setting the criteria of determining the correct gas model for helium-gas coolant leakage through a crack of the first wall operating under typical Tokamak fusion power reactor conditions. The representative pressure of helium gas at the plasma side is 0.013 Pa (10⁻⁴ torr), the pressure at the coolant side is 5 MPa (50 atmosphere) and the temperature of the gas is approximately at 500 °C. The crack width is to be 30 μm (considering the experimental specimens of 15 μm and 35 μm crack dimensions) for analysis purpose. The crack length used is 2920 μm.

1. Molecular Flow

Considering free molecular flow, the criteria are:

(a). According to Worden [1], if the product of characteristic equivalent dimension of the crack “a” in cm and the pressure of coolant $P_n$ in μm Hg is smaller than 5, then the flow is the molecular, i.e., if $aP_n < 5$ cm μm Hg, then it is the free molecular flow, but for our case,

\[ a = 30 μm = 3 \times 10^{-3} \text{ cm} \]
\[ P_n = 5 \text { MPa} = 3.8 \times 10^7 \text{μm Hg} \]

and $aP_n = 1.14 \times 10^5$ cm μm Hg $\gg 5$ cm μm Hg

(b). If the ratio of mean free path $L_{mf}$ to a characteristic dimension “a” (or the Knudsen Number), is greater than one, then the flow is the molecular type; i.e., if $L_{mf}/a > 1$ (or $K_n > 1$), it is the molecular flow.

Again, in our case $a = 30 μm$, and $L_{mf}$ is given by Patterson [2].

\[ L_{mf} = \frac{16}{5} \frac{\mu}{ρ\sqrt{2πRT}}, \]

where

\[ K_n = \text{Knudsen Number} = \frac{L_{mf}}{a} \]
\[ L_{mf} = \text{mean free path in m.} \]
\[ \mu = \text{viscosity of helium at 5 MPa and 500°C = 3.7 \times 10^{-5} kg/ms.} \]
\[ P = 5 \text { MPa.} \]
\[ R = 2077.02 \text{ J/kgK for helium} \]
\[ T = 773 K. \]
\[ ρ = 3 \text{ kg/m}^3. \]

Therefore, $L_{mf} = 0.012 \mu m$ and

\[ K_n = \frac{L_{mf}}{a} = 4 \times 10^{-4} \ll 1 \]

Therefore the flow is again not a free molecular flow by the second criterion.

2. Incompressible Viscous Flow

Consider incompressible viscous flow, i.e., the compressibility can be neglected in the treatment of the flow of gases if $(1/2)M^2 \ll 1$ [3]; then the flow can be considered to be incompressible, where $M$ is the Mach number.

For helium at 500°C, the sonic velocity $c$ is

\[ c = \sqrt{\frac{γRT}{\mu}} = \sqrt{\frac{1.667 \times 2077.02 \text{ J/kgK}}{773 K}} = 1636 \text{ m/s} \]

where $γ$ is the specific heat ratio, $R$ gas constant for helium, and $T$ absolute temperature of the gas, °K.

Assuming the flow through a crack opening is equivalent to that through a circular tube with equivalent radius, then the average flow velocity $V$ is

\[ V = \left( \frac{r_0^2}{8\mu} \right) \frac{(P_1 - P_2)}{L} \]

where $r_0$ is the radius of the opening, $L$ the length of the crack, $μ$ viscosity of helium at 500°C, $P_1$=coolant pressure at the inlet side, and $P_2$=coolant pressure at the exit.

In our case, since

\[ r_0 = 15 \mu m, \]
\[ L = 2920 \mu m, \]
\[ μ = 3.7 \times 10^{-5} \text{ kg/ms,} \]
\[ P_1 = 5 \text { MPa,} \]
\[ P_2 = 0.013 \text{ Pa,} \]