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Thermodynamic analysis of a high cooling capacity dilution refrigerator under the critical velocity limitation of the dilute phase

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The rapid development of superconducting quantum computing technology has stimulated the demand for cryogen-free dilution refrigerators with high cooling capacity. The method of increasing the mass flow rate to obtain a high cooling capacity is limited by the critical velocity of the dilute phase. This study delves into the operation of a high cooling capacity dilution refrigeration system, analyzing the enthalpy change from 0.7 K to 10 mK under the assumption of equal chemical potential of superfluid 4He, and subsequently establishes a thermodynamic analysis model. Through this model, the critical velocity limitation of the dilute phase is considered, and the effects of the dilution unit structures on the performance of a high cooling capacity dilution refrigerator are studied. Additionally, leveraging the real physical properties of 3He and 3He-4He mixtures, a comprehensive analysis is conducted on the pressure drop and viscous heating in the heat exchanger, particularly under critical velocity. This thermodynamic model furnishes robust support for designing and optimizing high cooling capacity dilution refrigerators.

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