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C1Po1D-05: Design and analysis of sub-K continuous heat exchanger for dilution refrigerators

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A continuous tube-in-tube heat exchanger (TTHx) is used to pre-cool the concentrated stream (99.9% He-3) from 700 to 100 mK (or below) using a dilute stream (6.4% He-3 and 93.6% He-4) in a dilution refrigerator (DR). In commercially available DRs, the inner tube carrying the concentrated stream in TTHx is helically wound (H-TTHx) to increase the compactness and improve the effectiveness. However, in literature, a helically wound inner tube is rarely modeled, and instead, a linear one-dimensional (1D) tube-in-tube (L-TTHx) geometry is used. Since both streams' enthalpy and thermal properties depend strongly on temperature, modeling of H-TTHx as L-TTHx will lead to deviations from the actual temperature profile along the length of H-TTHx. Consequently, the temperature profile of both streams and the effectiveness of TTHx remains to be determined.

In this study, we present the three-dimensional (3D) numerical analysis of a compact footprint (diameter < 5 cm and length < 10 cm, fixed by the space availability in DR) L-TTHx and H-TTHx manufactured using 70/30 Cu-Ni alloy under the constraint that the outlet temperature of the concentrated stream (Tco) remains less than 100 mK. Under the above geometry and temperature constraints, the maximum concentrated stream flow rate is limited to 200 and 400 µmol/sec for L-TTHx and H-TTHx. The 400 µmol/sec flow rate in the H-TTHx will lead to a base temperature of 10 mK in the mixing chamber and a cooling power of 15 µW or higher at 20 mK. We further explicitly determine the contribution of viscous heating, Kapitza resistance, and axial and radial conduction on the temperature profile along L- and H-TTHx and identify their relative contribution in controlling the effectiveness of TTHx. Contrary to the modeling assumption in the literature, if we maintain the same molar flow rate of the concentrated stream for L- and H-TTHx, the temperature profile along the length differs significantly in both decay rates along the length and the outlet temperatures. Our study highlights the need to go beyond the standard 1D modeling of H-TTHx used in DR as L-TTHx to precisely capture the temperature profile along the length and cross-section and determine the effectiveness of TTHx.

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