Impacts of Heat Exchanger Configuration on Water Production and Heat Storage in Membrane Distillation Systems Driven by Intermittent and Variable-Temperature Waste Heat Sources

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Direct contact membrane distillation (MD) is a water treatment process that can utilize low-grade waste heat as the driving force. In the scientific literature, low-grade waste heat is often idealized as having a constant temperature and being constantly available. However, characterization of multiple liquid- and gas-phase waste heat sources has identified inherent intermittency and thermal variability, which lead to unpredictable water flux and the possible need for heat storage to maintain driving force when the waste heat source is off. Waste heat characterization results will be presented that demonstrate these characteristics. To address challenges associated with waste heat intermittency and thermal variability, two heat exchanger configurations were evaluated through modeling and experiments.

In the direct configuration, feed solution is circulated from the feed tank, directly to the heat exchanger, then to the membrane module, and finally returned to the feed tank. In the indirect configuration, the feed solution is circulated from the feed tank, through the heat exchanger, and returned to the feed tank while simultaneously being circulated from the feed tank, to the membrane module, and returned to the feed tank in a separate circulation loop. These heat exchanger configurations were evaluated using modeling analyses and an experimental direct contact MD system with the ability to simulate variable-temperature waste heat sources using real-world data.

Modeling analyses were performed to evaluate the relative impacts of the two heat exchanger configurations on water production and heat storage when using intermittent waste heat sources. It was found that there exists a tradeoff between water flux and feed tank temperature (i.e., quantity of heat stored), with the direct configuration having an average of 17% higher water flux and the indirect configuration having an average of 13% higher feed tank temperature at steady state, over a range of flow rates. The indirect configuration was shown to have a rate of heat storage at least 59% higher than that in the direct configuration, at all feed tank temperatures greater than 35 °C, indicating that the indirect configuration can collect and store more heat in the potentially short time that it is available than the direct configuration. Time-varying water flux profiles will be presented for multiple scenarios with differing degrees of intermittency (i.e., ratio of time that the waste heat source is off to the time that the MD system is used). These water flux profiles demonstrate that the indirect configuration operates at higher water flux when the waste heat source is off while the direct

configuration operates at higher water flux when the waste heat source is on. The degree of intermittency was shown to affect which configuration was preferred, with the direct configuration producing 12% more water and the indirect configuration producing 6% more water with degrees of intermittency of 50% and 75%, respectively. Modeling results indicate that the indirect configuration may be preferred when degree of intermittency is high (e.g., 75%), but the direct configuration will be preferred when degree of intermittency is low (e.g., less than 50%), based on conditions tested.

Experimental analyses corroborate modeling results and enabled evaluation of the more thermodynamically complex scenario of variable-temperature waste heat. Experiments operated with a simulated intermittent waste heat source confirmed that the indirect configuration operates at higher water flux when the waste heat source is off and that the direct configuration operates at higher water flux when the waste heat source is on. Experiments operated using real-world variable-temperature waste heat data indicated that variability in the waste heat source temperature profile translates to variability in the water flux profile, resulting in 23% higher water flux variability with the direct configuration compared to the indirect configuration. The indirect configuration showed a delayed response of water flux to changes in waste heat source temperature of 18 minutes in a 24-hour experiment – identifying a forecasting capability that allows users to adjust operating variables (e.g., flow rates) before an expected decrease in water flux due to a decrease in waste heat source temperature. Experimental results indicate that the direct configuration should be used when operating with a variable-temperature (non-intermittent) waste heat source, but the indirect configuration could be preferred if a forecasting feature and more predictable (i.e., lower-variability) water flux is important for system users. These experimental and modeling results represent the first ever in-depth analyses of the roles of waste heat characteristics and heat exchanger configurations in MD system performance.