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Membrane distillation driven by intermittent and variable-temperature waste heat: System arrangements for water production and heat storage

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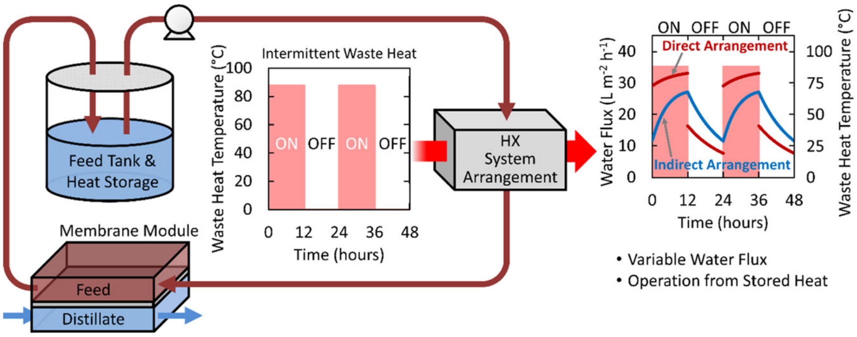
GRAPHICAL ABSTRACT



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ABSTRACT

The intermittency and variability inherent to many waste heat sources have largely been overlooked in existing studies of membrane distillation (MD). In the current study, MD system operation with intermittent and variable-temperature waste heat was assessed with two system arrangements: “direct” and “indirect.” In the direct arrangement, the heat exchanger and membrane module are in a single loop; in the indirect arrangement, they are in two separate loops. Modeling results indicate the direct arrangement produced 17.7% more water at 12.5% intermittency and the indirect arrangement produced 21.5% more water at 87.5% intermittency, due to the indirect arrangement's ability to store more heat when the waste heat source is on. Waste heat variability was strongly reflected in water flux profiles, but the indirect arrangement showed significantly less water flux variability – more than two times less in modeling analyses with intermittent waste heat and 30.4% less in variable-temperature experiments. Lower water flux variability in the indirect arrangement translates to better system controllability, even when the direct arrangement produces more water. The advantages of each arrangement identified in the current study give system designers key information to improve water production, heat storage, and/or system control in different waste heat scenarios.

1. Introduction

Membrane distillation (MD) is a thermally driven water treatment process that can be used in desalination [1–7] and water reuse [8–10] applications. In direct contact MD (DCMD), a warm feed solution (e.g., brackish water, seawater, wastewater, or other impaired water) is passed along one side of a hydrophobic, microporous membrane and a cooler distillate solution is passed along the other side. The temperature

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difference across the membrane induces a transmembrane vapor pressure difference, which causes water vapor to pass through the membrane pores and condense upon contact with the cool distillate stream. Benefits of MD include the ability to treat hypersaline solutions with minimal decrease in driving force [11], high rejection of non-volatile contaminants [12], the ability to use low-pressure system components with low capital cost and low safety concerns [13], and compatibility with low-grade waste heat as an energy source [4,14–17].

While definitions of "low-grade waste heat" differ between studies, the United States Department of Energy defines it as waste heat having a temperature between 25 and 150 °C, and estimates that 1222 trillion BTUs of low-grade waste heat are emitted each year in the United States alone [18]. This represents a significant and untapped source of energy. In particular, the fraction of low-grade waste heat emitted at temperatures < 100 °C, which is less useful for other heat recovery or waste-heat-driven processes, can be exploited by MD. Low-grade waste heat is available from many different energy processes in the power and industrial sectors. Power sector sources of low-grade waste heat include flue gas and cooling water from thermoelectric power plants [19,20], while industrial sources include kiln gasses and cooling streams in the cement and ceramic industries [21–25].

The inherently cyclic conditions and variable loads in industrial processes and power generation result in intermittent and variable supplies of waste heat. Thus, intermittency and variability are key considerations for a sizable fraction of the low-grade waste heat available for MD. Temperature profiles from example intermittent and variable-temperature waste heat sources were characterized for the current study (Fig. 1). Fig. 1a shows the temperature profile of flue gas from a natural-gas-fired boiler over a 24-hour period. The most striking characteristic of the temperature profile is the temperature cycling, or intermittency, caused by the boiler turning on and off depending on the heating demand. Fig. 1b shows the temperature profile of an industrial autoclave discharge. The autoclave discharge temperature profile shows significant temperature variability throughout the 24-hour period. Notwithstanding the data in Fig. 1, it is common practice to quantify waste heat availability using an average temperature and/or a single energy value that unintentionally obscures the variability and/or intermittency by lumping energy availability into a single bulk heat content value (for a finite time period) [24]. To provide a more realistic assessment of waste-heat-driven MD system operation, variability and intermittency must be decoupled from average temperature and bulk heat content values and evaluated for their individual impacts on MD system operation and control.

Existing waste-heat-driven MD studies have clearly demonstrated the ability to drive MD systems using waste heat and the potential economic competitiveness of such a strategy [14,17,26–35], but have not considered temperature variability or intermittency. Heat source variability was only mentioned in three studies of waste-heat-driven MD [14,28,33]; no implications were discussed. Temperature variability in these studies may have been low and therefore not particularly concerning, but the data in Fig. 1b provide clear evidence that waste heat variability can be significant. Variability in waste heat source temperature should be considered because it is likely to result in significant variability in water flux, which would result in low predictability of product water availability and could necessitate the use of more complex control systems. Waste heat intermittency (as shown in Fig. 1a) can have an even more significant effect on waste-heat-driven MD system performance by causing periodic losses of the thermal driving force required for continuous operation. To continuously operate MD systems and maintain product water availability even when the waste heat source is off, heat storage may be required. The limited literature discussing heat storage in MD systems is found in solar-thermal MD literature [2,36,37].

Heat storage has been integrated into solar-thermal MD systems through two main system arrangements: "direct" and "indirect." The direct and indirect terminology, coined by Banat et al. [38], is synonymous with the "single-loop" and "two-loop" terminology used in other solar-thermal MD studies. In the direct arrangement, feed solution is circulated in a single loop from the feed tank to the solar collector and through the membrane module [2,36,38–40]. Advantages of the direct arrangement include immediate delivery of the most recently heated feed solution to the membrane module, as well as low capital cost and compact system size. Disadvantages include the need for corrosion-resistant solar collectors that are much more expensive and less widely available than conventional collectors [41,42] and less system controllability associated with using a single pump to control heat extraction and membrane channel hydrodynamics. In the indirect arrangement, feed solution is simultaneously circulated through the membrane module in a "membrane loop" and through the solar collector in a separate "heat loop" [37,43–50]. The main advantage of the indirect arrangement is that it separates heat extraction and membrane module flow control, allowing higher flow rates to be used in the heat loop so that more heat can be extracted without affecting membrane channel hydrodynamics. The main disadvantage of the indirect arrangement is the higher capital cost associated with the extra pump required to have separate loops. If either the direct or indirect arrangement is used with an intermittent heat source (e.g., solar or waste heat), heat storage can be incorporated using the feed tank also as a heat storage tank.

All existing waste-heat-driven MD modeling and experimental studies have used the direct arrangement (Fig. 2a); none of these studies has considered heat storage needs in their analyses. The indirect

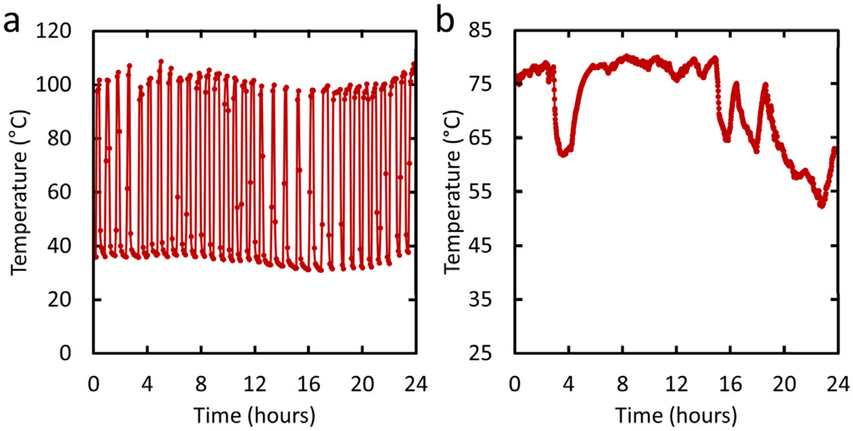

Fig. 1. Temperature profiles from example low-grade waste heat sources: (a) Intermittent temperature profile of flue gas from an industrial natural-gas-fired boiler and (b) variable temperature profile from an industrial autoclave discharge.