International Journal of Heat and Mass Transfer 127 (2018) 663–673

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Application of indirect non-invasive methods to detect the onset of crystallization fouling in a liquid-to-air membrane energy exchanger

Adesola Oluwasijibomi Olufade *, Carey James Simonson

Department of Mechanical Engineering, University of Saskatchewan, 57 Campus Dr., Saskatoon, SK S7N 5A9, Canada

ARTICLE INFO

Article history:
Received 15 February 2018
Received in revised form 4 June 2018
Accepted 5 June 2018

Keywords:
Onset of crystallization fouling
Indirect methods
Non-invasive methods
Moisture flux
Moisture transfer resistance
Membrane

ABSTRACT

Liquid-to-air membrane energy exchangers (LAMEEs) use semi-permeable membranes and are designed to transfer heat and moisture between air and liquid streams in heating, ventilating, and air-conditioning (HVAC) systems. However, crystallization fouling in membranes is possible in practical HVAC applications, and this may lead to severe degradation in the performance of LAMEEs.

The main aim of this paper is to apply three indirect non-invasive methods to detect the onset of crystallization fouling in a LAMEE. The methods are used to detect fouling by analyzing experimental measurements of moisture flux and moisture transfer resistance. The experimental tests involve dehydrating varying concentrations of $MgCl_2(aq)$ desiccant solutions using two types of membrane with different vapor diffusion resistances (VDRs).

The results confirm that two of the three methods can effectively detect the onset of crystallization fouling in the LAMEE. Thus, the methods can be used for online monitoring of operating LAMEEs in order to timely identify the initiation of fouling. The results also show that the membrane with a lower VDR produces a higher moisture flux which leads to a higher degree of fouling than the membrane with higher VDR.

1. Introduction

Fouling can be defined as the buildup of undesirable substances on a surface. Fouling negatively impacts the performance of engineering equipment, such as heat and membrane exchangers. Heat exchanger fouling is the attachment of particles to heat transfer surfaces, and reduces the overall heat transfer coefficient of heat exchangers [1]. Similarly, membrane fouling occurs when particles lodge on a membrane surface or within the membrane pores, and limit the permeation rate through the membrane [2].

Fouling results in additional power consumption, equipment oversizing, and maintenance and production losses [3–5]. Fouling also leads to severe economic consequences. It has been estimated that heat exchanger fouling costs about 0.25% of the gross domestic product of developed countries [3], which is approximately $5 billion CND for Canada in 2015, using data from The World Bank Group [6]. Furthermore, the economic impact of crude oil fouling in refineries has been assessed to be over 10 times greater than that of global heat exchanger fouling [7].

This paper is targeted towards fouling in heating, ventilating and air-conditioning (HVAC) systems, because HVAC systems play a key role in global energy consumption. In developed countries, HVAC systems make up about half of the energy consumed in buildings, and up to one-fifth of the total energy consumed [8]. In addition, the global demand for air-conditioning is expected to increase by over 30-fold between 2000 and 2100 [9].

Many studies on fouling in HVAC applications have focused on heat exchanger fouling (Refs. [10–18]), and only a few studies have addressed membrane fouling (Refs. [19–21]). Given that membranes are promising for HVAC applications and are progressively adopted in air-to-air heat/energy exchangers, two review papers (Refs. [22,23]) recently highlighted the need for extensive research on fouling in membrane-based HVAC systems. Woods [22] conducted a review of membrane adoption in HVAC applications, and suggested the need for additional research to address questions regarding the formation mechanisms and mitigation techniques for membrane fouling in HVAC systems. Abdel-Salam et al. [23] performed a comprehensive review of liquid-to-air membrane energy exchangers (LAMEEs), and recommended additional research on the impact of crystallization fouling on the performance of LAMEEs.

As documented in the aforementioned literature, fouling results in non-trivial technical and economic penalties, and therefore

* Corresponding author.
E-mail address: aoo021@mail.usask.ca (A.O. Olufade).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.032
0017-9310/

Nomenclature

Roman symbols

A_{mem}	membrane surface area (m^2)
C^*_{sol}	dimensionless solution concentration
d	discrepancy in the standard deviation of moisture flux or moisture transfer resistance between Groups 1 and 2
df	degree of freedom
F	performance parameter (*i.e.* moisture flux or moisture transfer resistance)
f_{sl}	criterion for fouling detection – slope method
f_{st}	criterion for fouling detection – statistical method
f_u	criterion for fouling detection – uncertainty method
$\dot{m}$	mass flow rate (kg/s)
M^*	normalized moisture flux
$\dot{m}''_v$	moisture flux ($g/(m^2{\cdot}h)$)
$\dot{m}''_{v,o}$	moisture flux at the start of the steady-state period of a test ($g/(m^2{\cdot}h)$)
n	number
P_{Slope}	random uncertainty in slope
R	moisture transfer resistance ($m^2{\cdot}s/kg_{air}$)
R^*	Normalized moisture transfer resistance
RH_{air}	relative humidity of air (%)
R_o	moisture transfer resistance at the start of the steady-state period of a test ($m^2{\cdot}s/kg_{air}$)
Slope	slope of a linear fit
$t_{df,95\%}$	critical t-value at the corresponding degree of freedom and a 95% confidence interval
t_{1-2}	t-statistic that is used to compare Groups 1 and 2
U	Total uncertainty at a 95% confidence interval
W	humidity ratio (kg_w/kg_{air})
ΔW_{lm}	log-mean humidity ratio (kg_w/kg_{air})

Greek symbols

σ	standard deviation

Subscripts

air	air
Group 1	control group where there is no fouling
Group 2	test group where fouling is examined
in	inlet of the LAMEE
$\dot{m}''_{v,Group\ 1}$	moisture flux of Group 1
$\dot{m}''_{v,Group\ 2}$	moisture flux of Group 2
n	number
o	start of the steady-state period of a test
out	outlet of the LAMEE
sol	salt solution or liquid water

needs to be properly understood and controlled. Fouling can be effectively mitigated if robust detection methods can be used to determine when fouling begins in exchangers. Different methods have been used to detect fouling, and previous reviews on various fouling detection methods can be found in Refs. [24–27].

In this paper, fouling detection methods are broadly divided into invasive and non-invasive categories. Invasive methods can directly confirm the presence of fouling particles but are usually disruptive to processes or require partial or complete disassembly of equipment. On the other hand, non-invasive methods can establish fouling without interfering with a process. Non-invasive methods are further divided into direct and indirect methods. Direct methods are used to directly identify the onset of fouling (*e.g.* observation of fouling using a microscope), whereas indirect methods are used to indirectly detect the start of fouling by analyzing measured parameters (*e.g.* temperature).

This paper addresses two gaps in the literature: the first gap is general and deals with fouling in heat and membrane exchangers, whereas the second gap focuses on fouling in membrane-based HVAC exchangers.

Firstly, there is a paucity of studies (*e.g.* Ref. [28]) that have used indirect non-invasive methods to detect the onset (*i.e.* start) of fouling in exchangers. On the contrary, many fouling studies use indirect non-invasive methods to detect if there is fouling during a test (*e.g.* increase in resistance [29–31] or decrease in flux [32–34]), and may afterwards confirm the presence and morphology of fouling using invasive methods such as scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) after the test. Consequently, these studies only confirm that fouling has occurred in a test, but do not determine the actual time that fouling started during the test. The delayed detection of fouling can result in significant damage to operating exchangers due to the accumulation of deposits.

Although some studies have used a direct non-invasive method (*e.g.* direct imaging of membranes in Refs. [35,36]) to determine the onset of fouling in exchangers, the implemented method is not suitable for operating exchangers in the industry due to installation challenges and lack of adaptability. In addition, the method in Refs. [35,36] is unable to indicate the performance of exchangers when fouling is detected. As such, there remains a need for indirect non-invasive methods that are both sensitive to detect the start of fouling in operating exchangers and adaptable to diverse process parameters (*e.g.* temperature, pressure, flux, effectiveness, etc.).

Secondly, there is a limited investigation of the onset of fouling in the specific area of this study (*i.e.* membrane exchangers for HVAC applications). Two studies assessed the occurrence of crystallization [19] and particulate [21] fouling in membrane exchangers using indirect non-invasive methods, but none of the studies determined the time of fouling initiation in the exchangers. Although Ref. [20] investigated the initiation of scale formation on a membrane using a direct non-invasive method (time-lapse photography), the camera used for imaging could only detect deposit particles within the limits of visual observation, and the images were captured at a minimum of 1-h intervals. Thus, the critical time that fouling started could not be estimated due to the limitations of the implemented method.

There is also a lack of study on the impact of membrane properties on crystallization fouling in membrane-based exchangers for HVAC applications. The studies of Refs. [19,20] addressed crystallization fouling in membrane exchangers for evaporative cooling by testing only one type of membrane and did not perform sensitivity analysis to identify the influence of any membrane property on the likelihood of crystallization fouling in a membrane exchanger. Consequently, the findings reported did not account for the differences that may arise from changes in the properties of the tested membranes.

This paper addresses the aforementioned research gaps through the application of indirect non-invasive methods to detect the onset of fouling. In this paper, the methods are applied offline to fixed data sets to detect the start of fouling in an exchanger. However, the methods can also be applied online to expanding data sets in order to early identify the start of fouling in operating