ELSEVIER
Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Membrane Science 250 (2005) 141–149
journal of MEMBRANE SCIENCE
www.elsevier.com/locate/memsci

Bulk and measured temperatures in direct contact membrane distillation

J.M. Rodríguez-Maroto[a], L. Martínez[b,*]

[a] Departamento de Ingeniería Química, Facultad de Ciencias, Universidad de Málaga, 29071 Málaga, Spain
[b] Departamento de Física Aplicada, Facultad de Ciencias, Universidad de Málaga, 29071 Málaga, Spain

Received 6 October 2003; accepted 20 September 2004

Abstract

The aim of this work is the development of a transport model for a direct contact membrane distillation process in laminar flow that allows knowing the velocity and temperature profiles within the flow channels as a function of externally measured temperatures just at the entrances and exits of the flow channels in the membrane module. The second aim is to apply this model to a conventional membrane module, and so calculate the difference between the bulk temperatures and the externally measured ones. For the system studied here, moderately important differences between both temperatures have been obtained when working at low flow rates and high temperatures. It can be concluded from the trends observed in this study that an estimation of this temperature difference has to be made before considering the bulk temperature as equal to the externally measured temperature, above all, in those systems where the thermal boundary layers represent an important portion of the flow channels height, and important temperature drops exist through them.

Keywords: Membrane distillation; Thermal boundary layer; Bulk temperature; Laminar flow; Transport model

1. Introduction

Membrane distillation (MD) refers to the thermally driven transport of water vapour through a porous hydrophobic membrane. Different experimental configurations of this process can be found in the literature [1]. In the configuration termed direct contact membrane distillation (DCMD), the membrane is placed between two aqueous liquid phases maintained at different temperatures. Due to the hydrophobic nature of the membrane, a liquid–vapour interface is formed at both ends of the membrane pores and a water-vapour pressure difference appears through the membrane. Consequently, water molecules evaporate at the hot interface, cross the membrane in the vapour phase, and condense in the cold membrane side, giving rise to a net water flux through the membrane.

The heat required for water evaporation at the membrane–liquid interface has to be supplied from the liquid hot phase. In a similar way, the condensation heat at the other membrane–liquid interface has to be removed to the liquid cold phase. This creates temperature gradients in the liquid films adjoining the membrane, known as thermal boundary layers. In this way, the temperatures in both liquid phases separated by the membrane change from the values on both membrane surfaces to the values outside the thermal boundary layers, known as bulk temperatures. All models in the DCMD literature assume the existence of the thermal boundary layers. So, for the calculation of the water vapour flux through the membrane it is necessary to know the temperatures on the membrane surfaces. However, in the MD modules, the hot and cold liquid phases are both usually flowing in narrow channels. Due to the small transversal dimension of these flow channels it is not possible to measure the temperature in the different regions of the channel. Typically, in a flat membrane module, four thermometers are placed out of the membrane module, just at the inlet and outlet of the hot and cold flow channels. In this way, when the theoretical results have to be compared with the experimental ones, it is necessary to know the temperatures on the

---

[*] Corresponding author. Tel.: +34 95 2131924; fax: +34 95 2132000.
E-mail address: lmartinez@uma.es (L. Martínez).

0376-7388/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.memsci.2004.09.046

membrane surfaces as a function of these externally measured temperatures.

Relative to this question, the majority of authors model permeation through the membrane using the dusty-gas model [2] and describe the heat transport in the feed and permeate channels and, therefore, the temperature polarization effects, in terms of film heat transfer coefficients [3–12]. These models allow the calculation of the membrane surface temperatures when the corresponding bulk temperatures are known, and they have been profusely used in the analysis of experimental results considering that the bulk temperatures are equal to the measured ones by the thermometers placed externally at the inlets and outlets of the membrane module. This approximation may be expected to be good when heat resistance in liquid phases is in very narrow stagnant boundary layers, that is, if flow is turbulent flow.

To consider the bulk temperature equal to the externally measured temperature can be a priori a rude approximation when the thermal boundary layers are thick and the temperature drop through them is high. In fact, it can be considered that, in a conventional flat membrane module, the measured temperatures at the inlets can be assumed equal to the bulk temperatures at the inlets of the hot and cold flow channels. But the measured temperatures at the outlets of the membrane module are "average" temperatures at the outlets of the flow channels, which could significantly differ from the bulk temperatures at the outlets of the flow channels if the thickness of the thermal boundary layer is important in relation to the height of the flow channel. This can be the case when laminar flow exists in the module channels.

None of the above mentioned models can be used to take into account that these temperatures differ, because they do not provide the velocity and temperature profiles in the liquid channels. The way to get to know these profiles is by solution of the momentum and heat transport equations in the liquid channels. Some authors [13,14] have developed procedures for a numerical solution of the mentioned equations, while others [15,16] have obtained analytical solutions making some assumptions. Due to its higher simplicity, here an analytical solution has been preferred, and so a model is shown based on a different analytical solution of transport equations obtained from assumptions acceptable in the experimental system studied, and obtained considering its finality: to know the distillate flux as a function of the externally measured temperatures and calculate the difference between bulk and externally measured temperatures in a membrane module with flat-sheet geometry.

2. Experimental

Experimental tests were conducted with a commercial hydrophobic flat-sheet membrane manufactured by Gelman Instrument and marketed as TF200. This membrane is made of polytetrafluoroethylene (PTFE), supported by a polypropylene net. Its principal characteristics, as specified by the manufacturer are: pore diameter 0.2 μm; thickness 60 μm; fractional void volume 80%. Deionised and distilled water was used in the experiments.

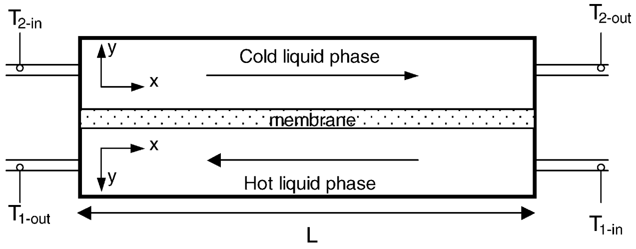

Fig. 1. Membrane module including the membrane and the hot and cold liquid phases. The four thermocouples placed at the entrances and exits are shown.

A detailed description of the experimental device used may be found in [17]. Its central part is the membrane module that consists of prismatic flow channels made with silicone separators placed between two acrylic manifolds. The membrane was placed between the silicone separators and the flow channel dimensions were bxHxL = 0.45 mm × 7.0 mm × 55 mm. Hot and cold liquid water flowed tangentially on both sides of the membrane at the same flow rate and in counter current mode. In the following the subindex 1 and 2 will refer to hot and cold liquid phases, respectively. The temperature of the water was measured at the inlets ($T_{1\text{-in}}$ and $T_{2\text{-in}}$) and outlets ($T_{1\text{-out}}$ and $T_{2\text{-out}}$) of the membrane module (Fig. 1). In the experiments ($T_{1\text{-in}} - T_{1\text{-out}}$) and ($T_{2\text{-out}} - T_{2\text{-in}}$) were between 0.5 and 1.3 °C.

In each experiment the temperatures at the inlets of the module were maintained constant. The mass flux through the membrane and the temperatures at the exits of the module were measured when steady conditions were achieved. Different experiments were carried out for different inlet temperatures and flow rates on both sides of the membrane.

3. Theory

The system to be studied consists of a porous hydrophobic membrane, which is held between two symmetric channels. Hot water is circulated through one of the channels and cold water through the other one. The hot and cold fluids counter-flow tangentially to the membrane surface in a flat membrane module. The temperature difference through the membrane gives rise to a water vapour pressure difference and, consequently to a water flux, J, through the membrane. The heat requirements for water evaporation at the membrane–liquid interface have to be supplied from the hot liquid phase. In the same way, the condensation heat at the other membrane–liquid interface has to be removed to the cold liquid phase. This creates temperature gradients in the liquid films adjoining the membrane. This phenomenon is called temperature polarization along the coordinate perpendicular to the membrane, which will be considered as y coordinate. This means that the temperatures at the limit of the