

**International Workshop on
Membrane Distillation
and Related Technologies**

October 9 - 12, 2011

***Auditorium Oscar Niemeyer
Ravello (SA) - Italy***

Proceedings



organized by the
Institute on Membrane Technology (ITM-CNR)

in collaboration with the

***Dept. of Chemical Engineering and Materials
University of Calabria***



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Edited by E. Drioli, G. Di Profio, M.A. Liberti

International Workshop on Membrane Distillation and Related Technologies

Auditorium Oscar Niemeyer, Ravello (SA) – Italy

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A novel TLC based technique for temperature field investigation in MD channel

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Introduction

The importance of temperature polarisation phenomenon in the performance analysis of the Membrane Distillation (MD) process has been recently raised by several researchers. A number of studies have focused on the study of this phenomenon at a macroscopic scale looking at average values of temperature and fluxes [1-2], but none of them has presently investigated the spatial distribution of temperatures on the membrane surface, which could be a fundamental information for the choice of the best geometrical features of a spacer. Some CFD works have been presented in the literature [3] aiming at the local thermo-fluid dynamics characterisation of spacer filled channels, but no validation of model predictions with experimental information has been presented yet.

In the present work a novel experimental technique, based on the use of Thermo-chromic Liquid Crystals (TLCs), has been developed and used for the investigation of temperature distribution inside a spacer-filled MD channel.

Experimental

The experimental apparatus (Fig. 2) consisted in a double channel, entirely realised in plexiglass[®], which simulated the presence of the hot and cold channel of a Direct Contact MD module. The membrane was substituted by a thin (1mm) polycarbonate sheet, which allowed conductive heat flux (thus simulating the conductive and convective heat fluxes across the hydrophobic membrane). Hot and cold streams temperatures were regulated by thermostatic buffers and monitored by a DAQ equipped with thermocouples T-type. Flow rate of the hot stream was measured by a digital magnetic flow meter, while for the cold stream a rotameter was used. A TLCs sheet (Hallcrest[®] R30C5W) was glued on the hot side of the polycarbonate surface in order to measure temperatures at the hot interface.

Three different spacers were tested. Relevant pictures are presented in Fig.1, while geometrical features are shown in Table 1, reporting the wire inclination with respect to the main flow direction, wires diameter, wires spacing, voidage degree and hydraulic diameter.

Table 1. List of geometric features of spacers in exam

Spacer	h_{ch} [mm]	θ	d_{w1} [mm]	d_{w2} [mm]	l_{m1} [mm]	l_{m2} [mm]	Voidage ϵ	d_h [mm]
<i>Tenax-A</i>	3	45°	2	1	5.2	4.4	0.63	1.53
<i>Tenax-B</i>	3	0°	2	1	5.2	4.4	0.63	1.53
<i>Super-Tenax</i>	5	45°	3.2	2.5	12	10.5	0.68	3.18
<i>Diamond</i>	3.5	45°	2	1.8	11	11	0.85	3.86

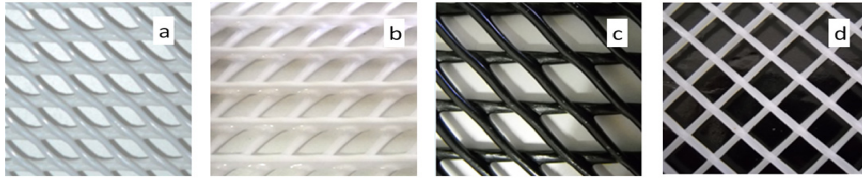


Figure 1. Photos of tested spacers: a) Tenax-sideA, b)

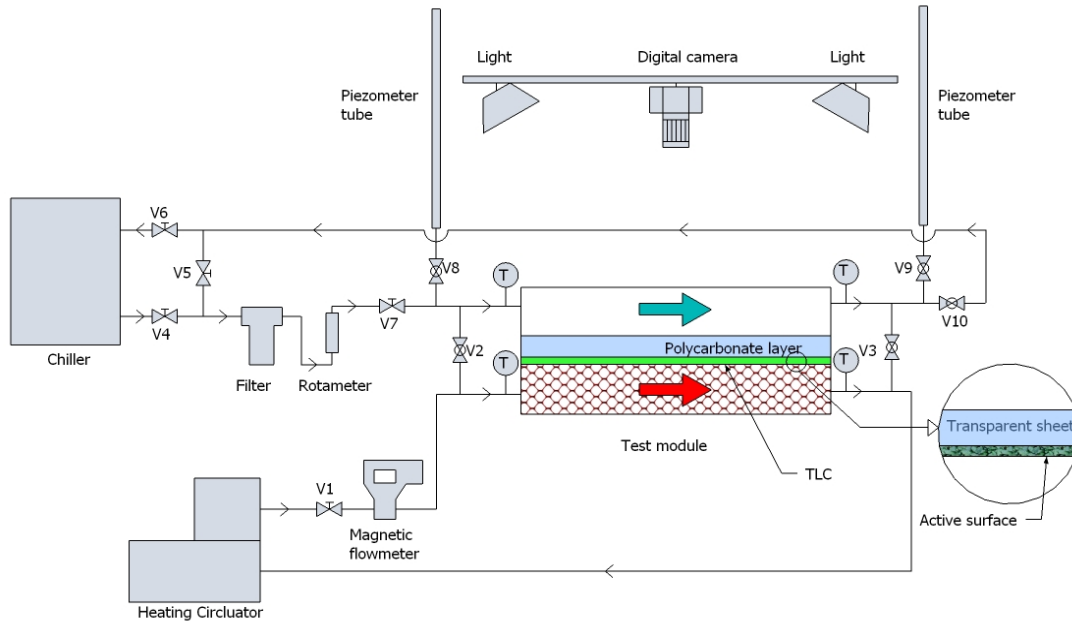


Figure 2. Experimental set-up.

Temperature maps were recorded by a high resolution digital camera and then post-processed using the Matlab[®] *Image Processing Toolbox*. An *in situ* calibration (Fig.3) was performed in order to relate the Hue component of the coloured image to the measured temperature at the TLC surface.

For each spacer, the hot-side flow rate was varied from 60 l/h to 160 l/h and about 25 pictures were acquired at a frequency of 0.2 Hz always monitoring the liquid temperature in both channels.

Collected data was used to evaluate local temperature distribution and polarisation. Once bulk temperatures of hot and cold fluids and the cold-side heat transfer coefficient are known (assuming, in this case, a laminar regime in the cold channel), the hot-side heat transfer coefficient h_h can be derived from the measured temperature T_l of the TLC sheet under the assumption of one-dimensional heat transfer, as suggested by Eq.(1), obtained by conveniently writing and arranging the equations for the heat flux within each part of the test-module:

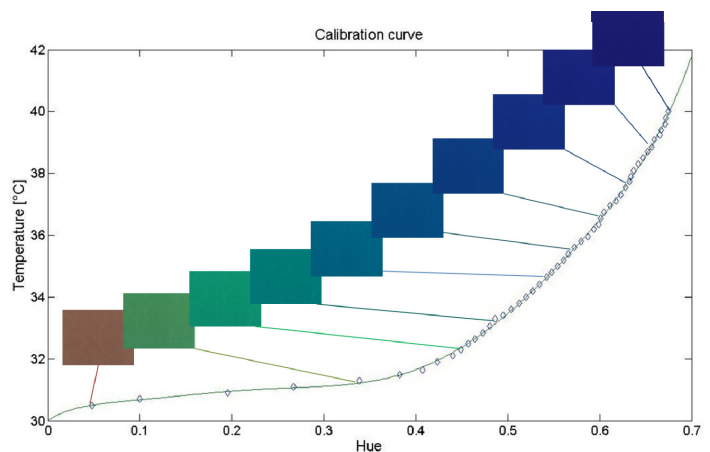


Figure 3. Calibration curve for TLC sheet adopted during experimental tests.

$$h_h = \frac{T_i - T_c}{(T_h - T_i) \left(\frac{L_{TLC}}{\lambda_{TLC}} + \frac{L_{Pol}}{\lambda_{Pol}} + \frac{1}{h_c} \right)} \quad (1)$$

where T_h and T_c are the bulk temperatures of the hot and cold channel, T_i is the TLC active face temperature, L_{TLC} - L_{Pol} and λ_{TLC} - λ_{Pol} are the thicknesses and the thermal conductivities of the TLC and polycarbonate sheet respectively, and h_c is the heat transfer coefficient in the cold channel. Finally all the information collected can be used also to estimate the local heat flux distribution on the wall surface simulating the membrane.

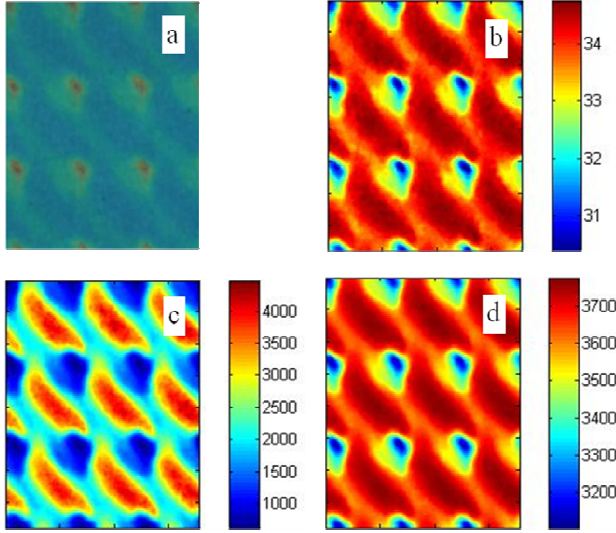


Figure 4. Images obtained with Tenax-A spacer, fluid flows from the right-hand side to the left, a) Typical test region showing TLC surface; b) Distribution of local temperature [in °C] on TLC surface; c) Distribution of local hot-side heat transfer coefficient (in W/m^2K); d) Distribution of local heat flux.

On the whole, the test section included a large number of repetitive elementary spacer cells (from 60 to 750 according to the spacer type investigated). Statistics were performed on the measured distributions in order to obtain a representative average unit cell, for which the average values of the above parameters were computed and their spatial distribution derived.

Figures 4.a-b show a typical test region, which contains 9 repetitive unit cells of a Tenax-A spacer, and the relevant temperature map obtained. Figures 6.c-d show the local heat transfer coefficient and local heat flux distributions, both averaged on the number of test regions considered in each image.

By analysing the images recorded with reference to the actual position of wires it is possible to identify different regions characterized by:

- Minimum temperature/heat transfer coefficient ($h_h < 1500 W/m^2K$ in Fig. 6c) in correspondence with the contact area between spacer and TLC sheet, where heat transfer by convection is inhibited by the physical presence of the spacer, allowing conductive heat transfer only;
- Medium-low temperature/heat transfer coefficient ($1500 < h_h < 3000 W/m^2K$ in Fig. 6c) downstream of oblique wires and, particularly, behind contact areas due to the presence of calm zones and low fluid velocity;

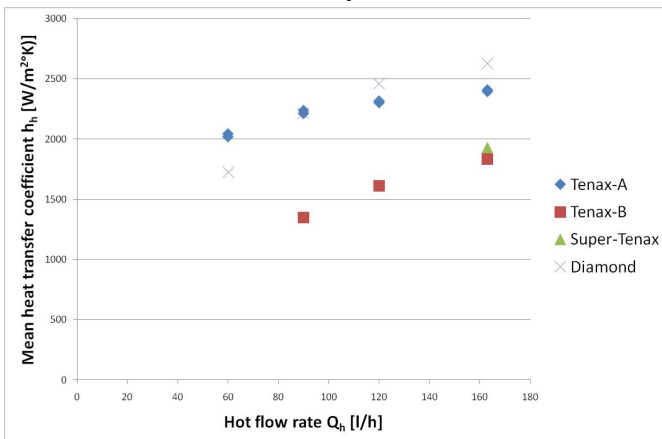


Figure 5. Mean heat transfer coefficient versus hot channel flow rate: comparison between different spacers.

- High temperature/heat transfer coefficient ($h_h > 3000 W/m^2K$ in Fig.6c) in the centre of each unit cell where mixing promotion is enhanced thanks to a significant presence of velocity components perpendicular to the conductive wall.

Comparison between spacers

Comparison among spacers has been done considering only the average values of heat transfer coefficients. Fig. 5 shows how the mean heat transfer coefficient varies with the hot water flow rate for the tested spacers (Super-Tenax spacer was tested with only one value of flow rate). As expected, higher h_h are reached when the flow rate is higher,

i.e. with higher velocity. Tenax-A and Diamond, both with oblique wires close to the conductive wall, seem to present higher h_h within the range analyzed, with respect to Tenax-B. This may be related to the fact that oblique wires better promote mixing inside the channel, although that is not in complete agreement with previous literature findings [3].

An important comparison can also be done by plotting the Nusselt number versus Reynolds number calculated on the basis of mean fluid speed and channel height, as shown in Fig. 6. Data are compared with the Nusselt number in an equivalent empty channel, and a value of 5.38 was calculated by analytically solving the heat transfer equation for a rectangular channel confined by an adiabatic wall on one side and a conductive wall on the other. All the spacers give rise to higher Nusselt numbers compared to the equivalent empty channel, thus confirming how the presence of the spacer enhances heat transfer by promoting mixing conditions. Even though mean heat transfer coefficient for Diamond and Tenax-A spacers are quite close to each other, Nusselt numbers for Diamond spacer are higher than for Tenax-A at all Reynolds numbers considered here. This can be explained by a larger thickness of the Diamond spacer compared to Tenax-A (3.5mm vs. 3.0mm), leading to a higher hydraulic diameter, which directly influences the Nusselt number estimation. For the same reason, the Super-Tenax spacer presents a high Nusselt number even if the corresponding mean heat transfer coefficient is quite low, due again to the larger thickness (5mm) of this spacer.

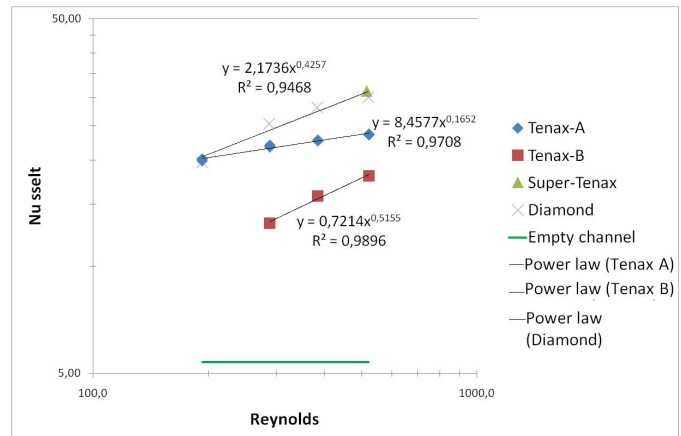


Figure 8. Nusselt number *versus* Reynolds number: comparison between different spacers.

Conclusions

A space-resolved thermographic technique based on thermochromic liquid crystals (TLCs) was developed in order to estimate temperature-polarisation and local heat transfer coefficient distribution inside spacer-filled channels for Membrane Distillation modules. A purposely designed experimental apparatus was set-up and preliminary used for testing different spacer configurations. Raw images were recorded and post-processed using the Matlab® Image Processing Toolbox. The technique proved to be able to characterize the local distribution of temperatures on the membrane surface, heat transfer coefficients and heat fluxes and correlate them to geometrical features of each spacer.

Further investigations will be performed in order to fully characterize mixing and heat transfer phenomena promotion in spacer-filled channels for Membrane Distillation modules.

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