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Experimental and computational investigation of heat transfer in channels filled by woven spacers

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ABSTRACT

Models of woven-type spacer-filled channels were investigated by Computational Fluid Dynamics (CFD) and parallel experiments in order to characterize the performance of Membrane Distillation (MD) modules. The case of overlapped spacers was analysed in a companion paper.

Experiments were based on a non-intrusive technique using Thermochromic Liquid Crystals (TLC) and digital image processing, and provided the distribution of the local convective heat transfer coefficient on a thermally active wall. CFD simulations ranged from steady-state conditions to unsteady and early turbulent flow, covering a Reynolds number interval of great practical interest in real MD applications. A specific spacer aspect ratio (pitch-to-channel height ratio of 2) and two different spacer orientations with respect to the main flow (0° and 45°) were considered.

Among the existing studies on spacer-filled channels, this is one of the first dealing with *woven* spacers, and one of the very few in which *local* experimental and computational heat transfer results are compared. Results suggest a convenience in adopting the 45° orientation for applications that can be operated at very low Reynolds numbers, since convenience decreases as the Reynolds number increases.

1. Introduction

1.1. Spacer-filled channels

Several membrane-based processes, e.g. Membrane Distillation [1], Reverse Osmosis [2] and Reverse Electrodialysis [3], involve flow and heat or mass transfer in spacer-filled plane channels. Spacers serve the double purpose of maintaining the appropriate distance between the channel walls and promoting mixing, thus reducing polarization and increasing transfer rates [4].

Applications differ in size (channel height from 10^{-4} to 10^{-2} m), flow regime (from creeping to turbulent) and quantity being transferred (heat, water, ions etc.), but involve comparable spacer geometries. For example, Fig. 1 reports examples taken from three families of net spacers (extruded, overlapped, woven) which have been paid particular attention in the literature. More complex spacer shapes have also been proposed [5–7].

Overlapped wire spacers have been the subject of a previous study by our research group [8]. Recently obtained experimental and computational results for woven spacers are presented here.

1.2. Literature review

Temperature polarization may severely impair the performance of MD modules [9]. Spacers interposed between the walls of a plane channel promote mixing and reduce polarization, thus enhancing heat or mass transport and reducing fouling issues [4,10]. Unfortunately, they also cause pressure drop to increase [11]. Thus, much research effort has been devoted to the search for spacer configurations offering a compromise between heat or mass transfer and hydraulic losses [8,11–15].

Different applications of spacer-filled channels are characterized by different spatial scales and flow rates, and thus the flow regimes expected are different. For example, low Reynolds number steady-state flow is typical in Reverse Electrodialysis, whereas unsteady and turbulent flow may occur in Membrane Distillation. It should be kept in mind that, in the complex flow passages created by spacers, the base steady state flow may well lose stability at critical Reynolds numbers of a few hundreds, much lower than those holding in plane channels and other simple ducts [8,16].

The literature is poor of results for woven spacers. What can be said is that woven spacers, either of the simple type in Fig. 1(c) or more complex, seem to provide better heat/mass transfer performances than overlapped spacers in MD and other membrane

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Nomenclature

Symbol	quantity
D_h	"Void" hydraulic diameter, $2H$
d	spacer filament diameter ($=H/2$)
f	darcy friction coefficient
h	heat transfer coefficient, $q''_w/(T_b - T_w)$
H	channel height
l	spacer filament pitch
Nu	Nusselt number, hD_h/λ
Pr	Prandtl number
Q	volume flow rate
q''_w	wall heat flux
r	overall external thermal resistance
Re	bulk Reynolds number, UD_h/ν
Re_τ	friction velocity Reynolds number, $u_\tau(H/2)/\nu$
s	thickness
T	temperature
U	mean velocity in the void channel, $Q/(HW)$
u, v, w or u_j	velocity components along x, y, z
u_τ	friction velocity
W	channel spanwise extent
x, y, z	Cartesian coordinates

Greek symbols

θ	angle formed by the spacer with the main flow
λ	thermal conductivity
μ	viscosity
ν	kinematic viscosity, μ/ρ
ξ	distance along the flow direction
ρ	density
τ_w	wall shear stress

Subscripts

b	bulk
c	cold
h	hot
poly	polycarbonate sheet
TLC	Thermochromic Liquid Crystals
w	wall (=hot side of TLC layer)
ξ	main flow direction

Averages

$\bar{\Phi}$	time average of the generic quantity Φ
$\langle\Phi\rangle$	space average (e.g. on a plane) of Φ

processes [17]. Unfortunately, also pressure drops are significantly higher [18].

In recent years, Computational Fluid Dynamics (CFD) has been increasingly employed to investigate flow field and transport features in spacer-filled channels. Once properly validated against experimental data, CFD provides valuable local information on both existing spacers and novel ones. While most CFD studies have limited the analysis to the *steady* regime [10,19–23], a few have been devoted to the CFD simulation of *unsteady* flows. For example, Koutsou et al. [16] performed Direct Numerical Simulations (DNS) highlighting that unsteadiness may occur even at low Reynolds numbers; Mahdavifar et al. [24] employed DNS to investigate the effects of the spacer-to-wall clearance on the flow field; and Tamburini et al. [8] simulated early turbulent flow in channels filled with overlapped-type spacers using DNS. At high Reynolds number, DNS can become too computationally expensive, and the use of a turbulence model may be more suitable. For example, Shakaib et al. [25] employed the Spalart–Allmaras model (based on a single transport equation for the turbulent viscosity) to predict temperature polarization in Membrane Distillation modules.

1.3. The issue of CFD validation

The problem of CFD results validation in geometrically or physically complex problems deserves a brief discussion. Steady-state, laminar flow simulations, provided mathematical consistency and grid-independence are demonstrated, do not really require being validated against experimental data, since they are potentially more accurate than any possible experiment and, at most, should be compared with analytical solutions (if any exists) or with previous numerical simulations of demonstrated high accuracy.

Rather, the real purpose of a comparison between CFD predictions and experimental results should be to check to what extent the complexity of the actual physical system is sufficiently reflected in the computational model, i.e. to quantify the influence of assumptions like neglecting minor geometrical irregularities or describing the actual flow and thermal boundary conditions as canonical (Dirichlet, Neumann or Cauchy) ones.

In this respect, local data, e.g. the 3-D flow and thermal fields and the distribution of the heat transfer coefficient on a thermally active wall, are more useful than *global* experimental results like the friction coefficient and the mean heat transfer coefficient. We

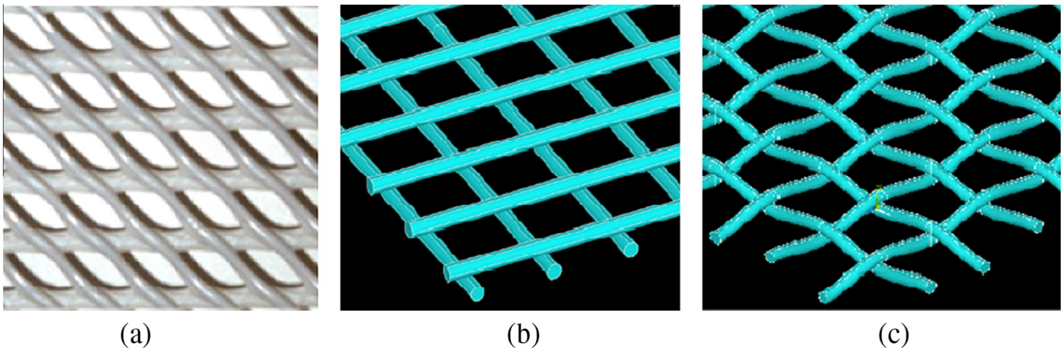
(a) (b) (c)

Fig. 1. Different families of net spacers: (a) extruded; (b) overlapped; (c) woven.