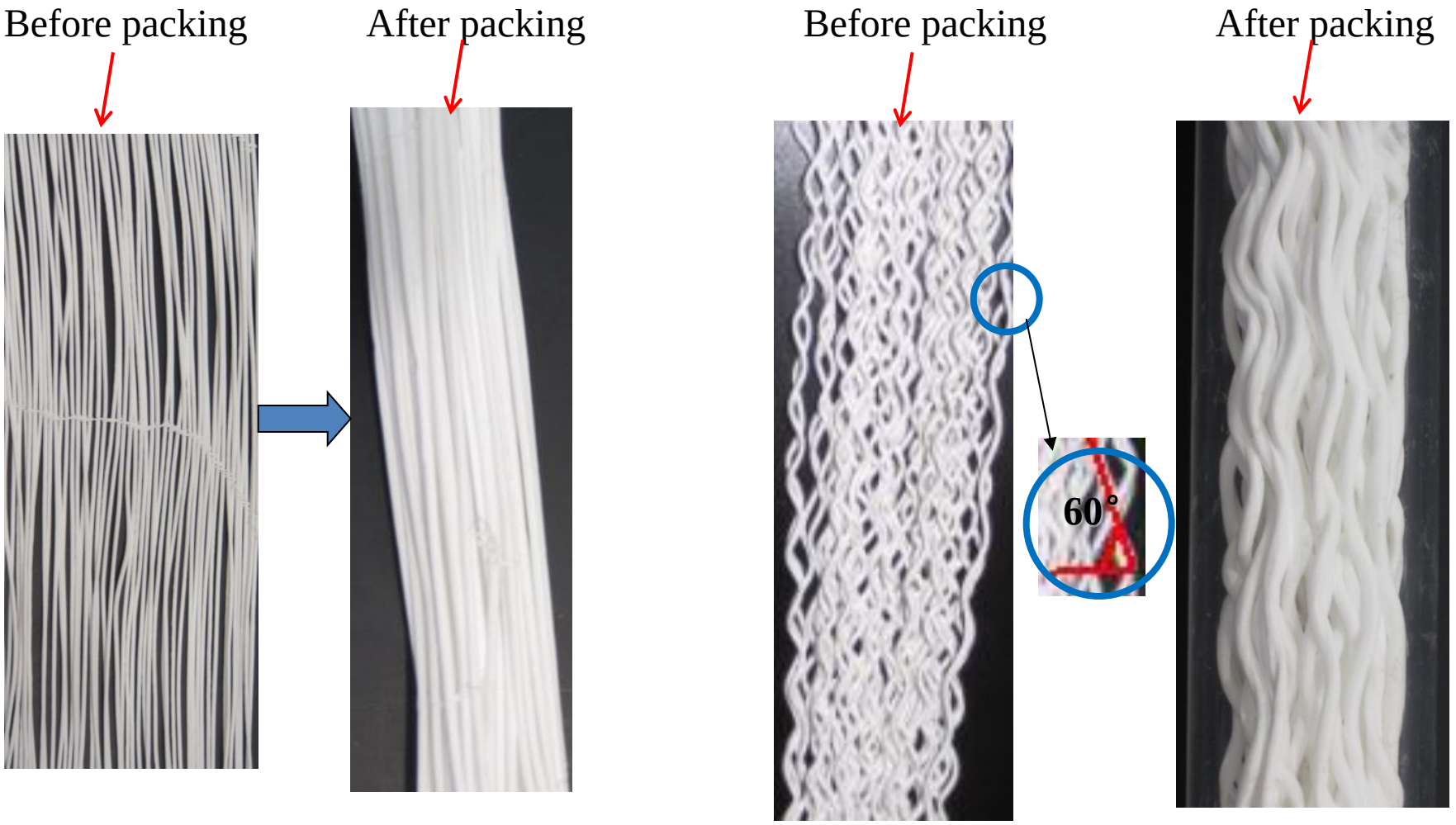
Novel designs for improving the performance of hollow fiber membrane distillation modules

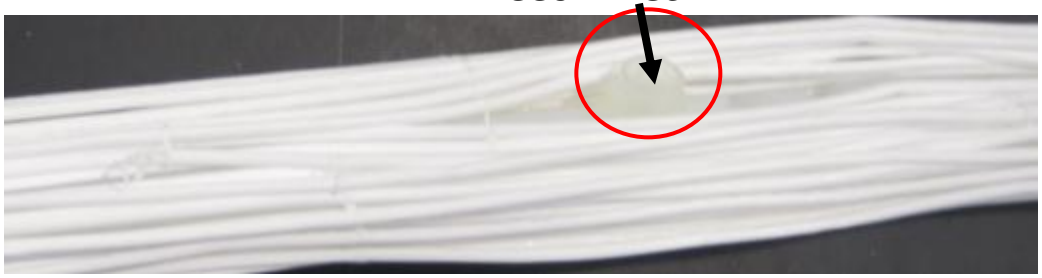


(a) structured-array module

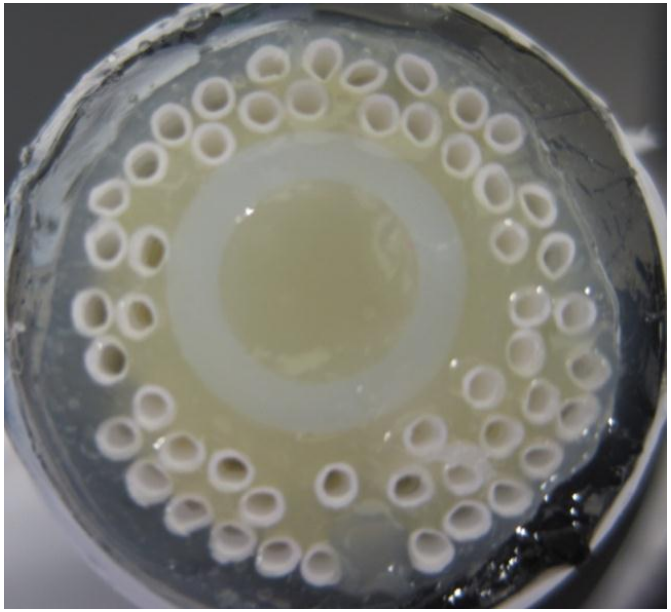
(b) Curly-fiber module

Before packing

Feed inlet



After packing

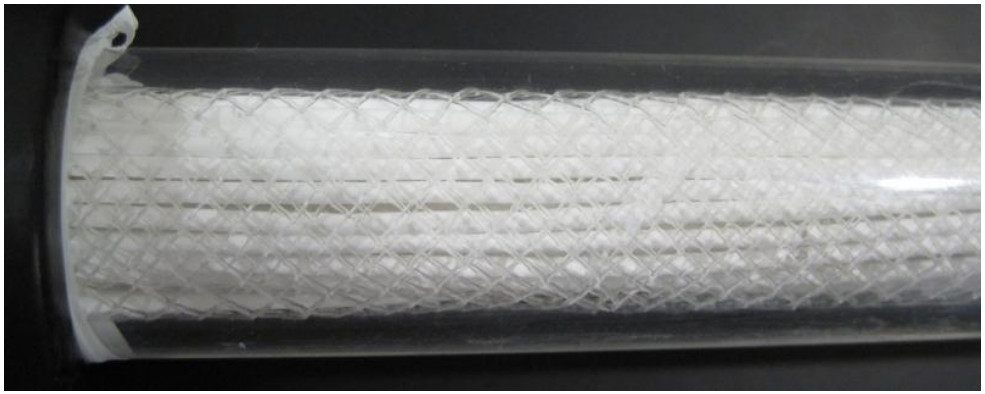


Cross section

(c) Central-tubing module

Before packing

After packing



(d) Spacer-wrapped module

(e) Spacer-knitted module

Fig. 1. Novel module design and fabrication:
(a) Structured-array module; (b) Curly-fiber module; (c) Central-tubing module;
(d) Spacer-wrapped module; (e) Spacer-knitted module

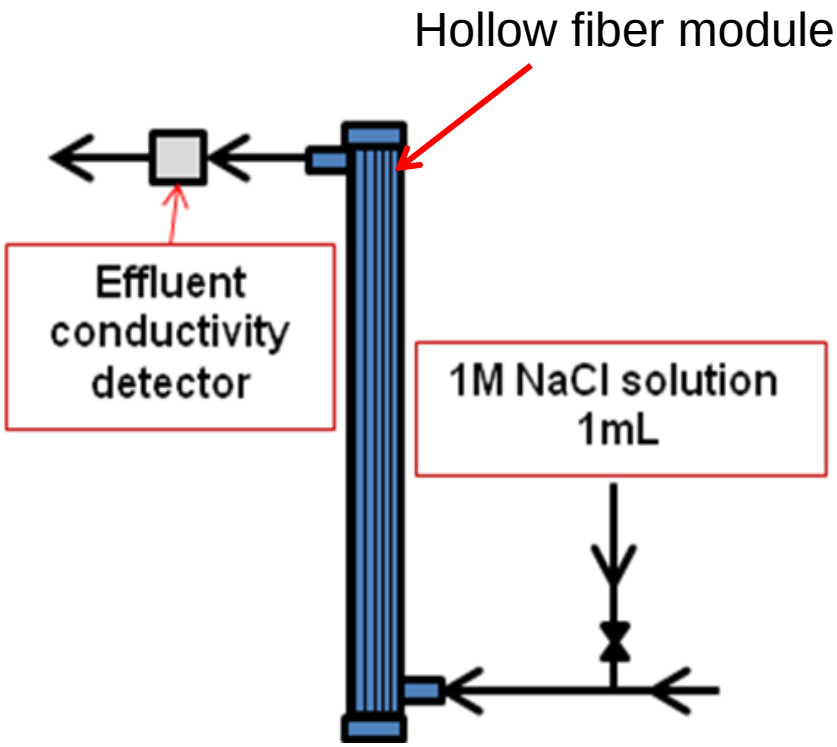


Fig. 2. Schematic of tracer-response experiment

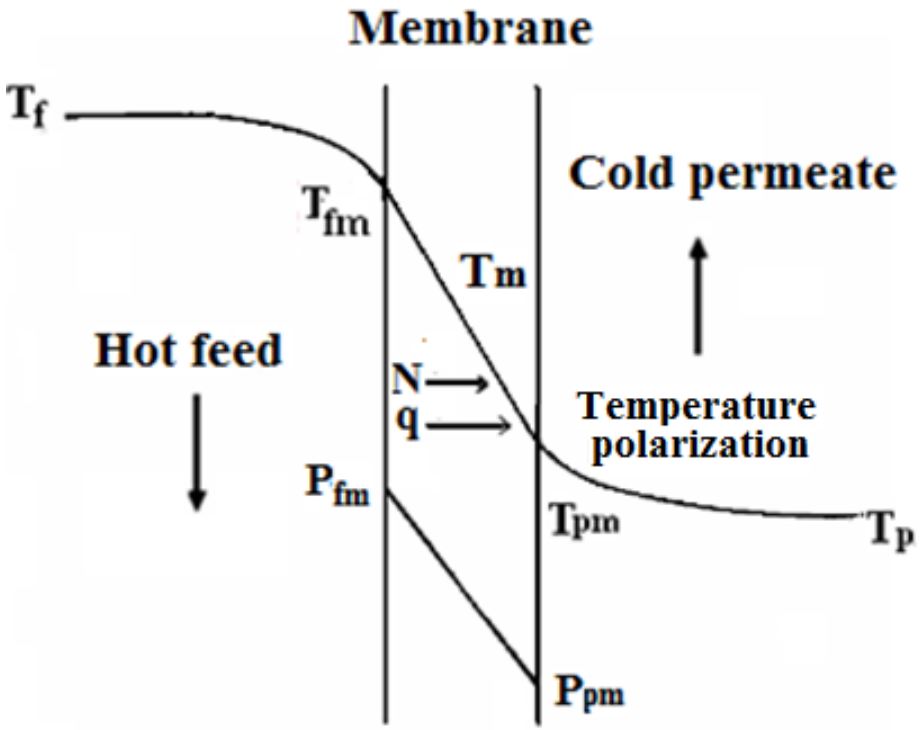
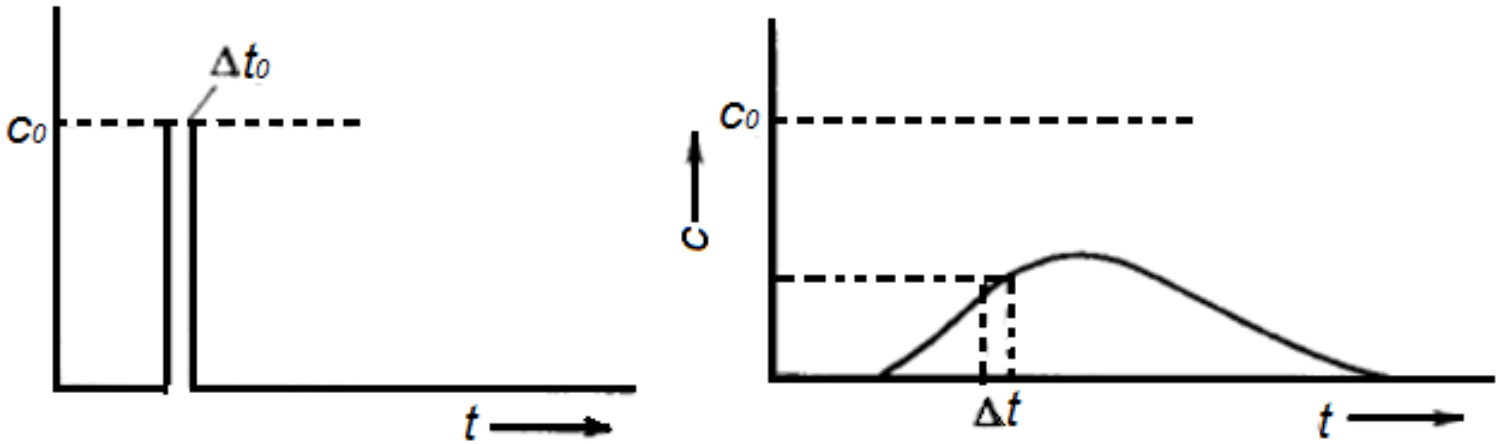


Fig. 3. Temperature and pressure profiles in MD



(a) (b)

Fig. 4. The tracer-response concentration at different exit times
for pulse tracer injection flowing through a vessel filled with liquid: (a) pulse injection of tracer with concentration of C_0 into the fluid entering the vessel at time Δt_0; (b) effluent concentration curve $C\ (t)$
(no chemical reaction or adsorption occurred)

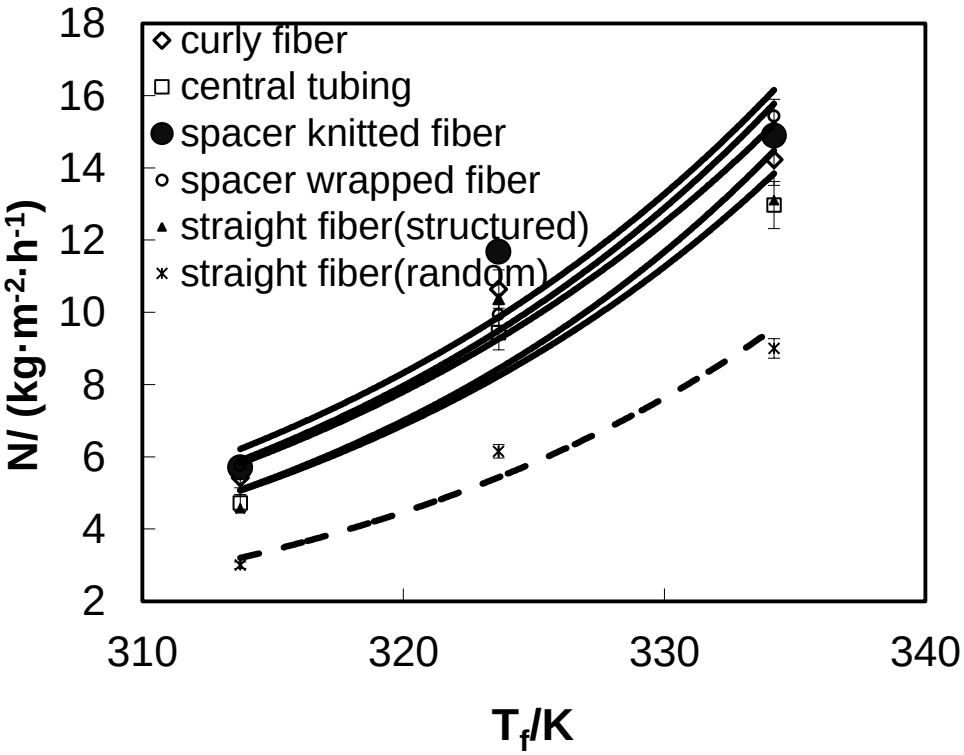


Fig. 5. Effect of feed temperature on the permeation flux for various hollow fiber module configurations [3.5% NaCl solution as feed Q_f =3 L·min^{-1}(v_f =0.33m·s^{-1}), Q_p =0.4 L·min^{-1} (v_p =0.08m·s^{-1}), T_p =298K, T_f =313-333K]

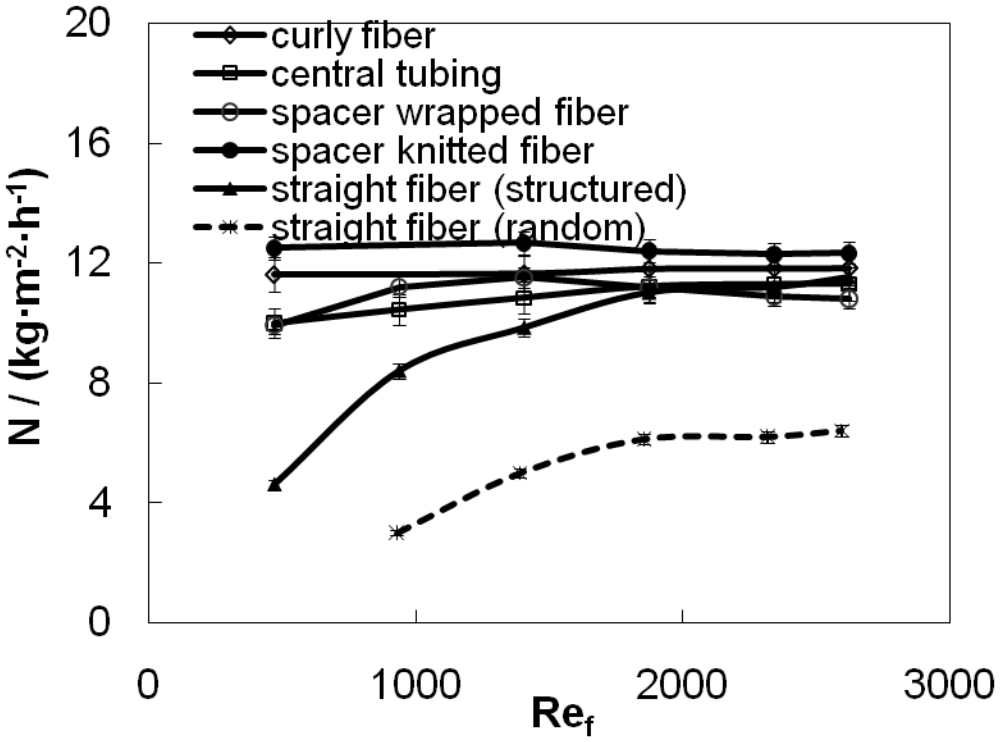


Fig. 6. Effect of recirculated feed velocity on permeation flux
(3.5% NaCl solution as feed v_f =0.08~0.47 m·s^{-1} (1-5.6 L·min^{-1}), v_p=0.08 m·s^{-1}, T_p =298K, T_f =323K)

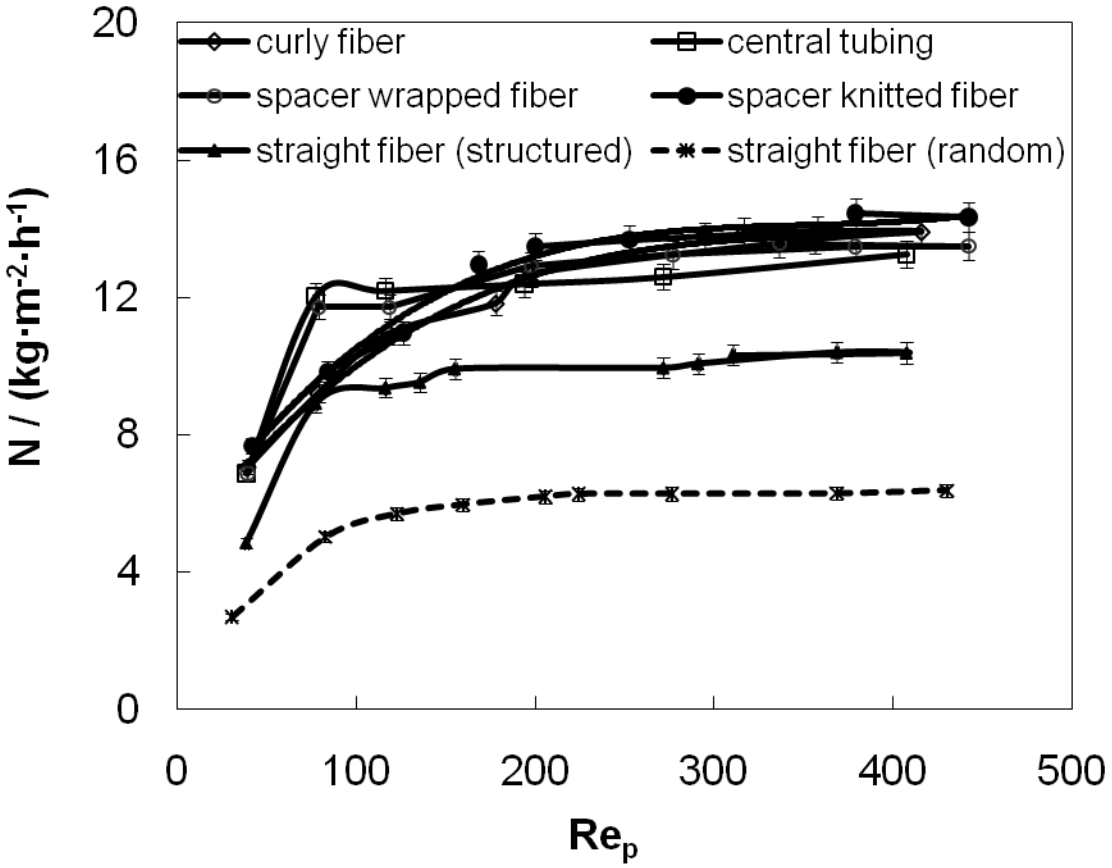


Fig. 7. Effects of recirculated permeate velocity for various hollow fiber module configurations [3.5% NaCl solution as feed Q_f =4 L·min^{-1}(v_f =0.33 m·s^{-1}), Q_p =0.1-2.1 L·min^{-1} (v_p <0.5 m·s^{-1}), T_p =298K, T_f =323K)]

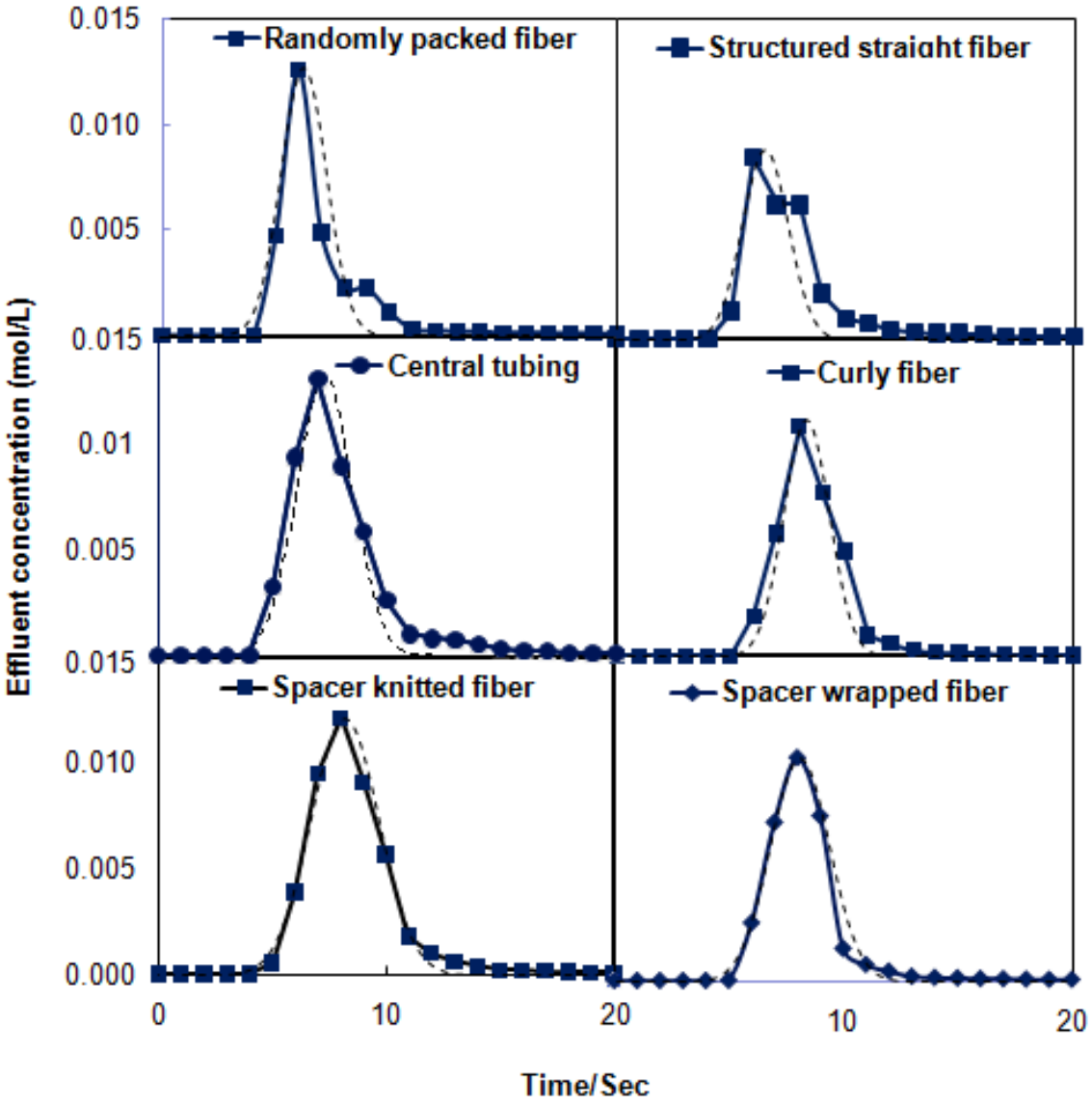


Fig.8. RTD concentration *C(t)* response curves for various configurations in tracer tests (Background solution: pure water; tracer: sodium chloride solution, 1mol/L; amount: 1mL; Q_f =2.5 L·min^{-1}, T_f=298 K)

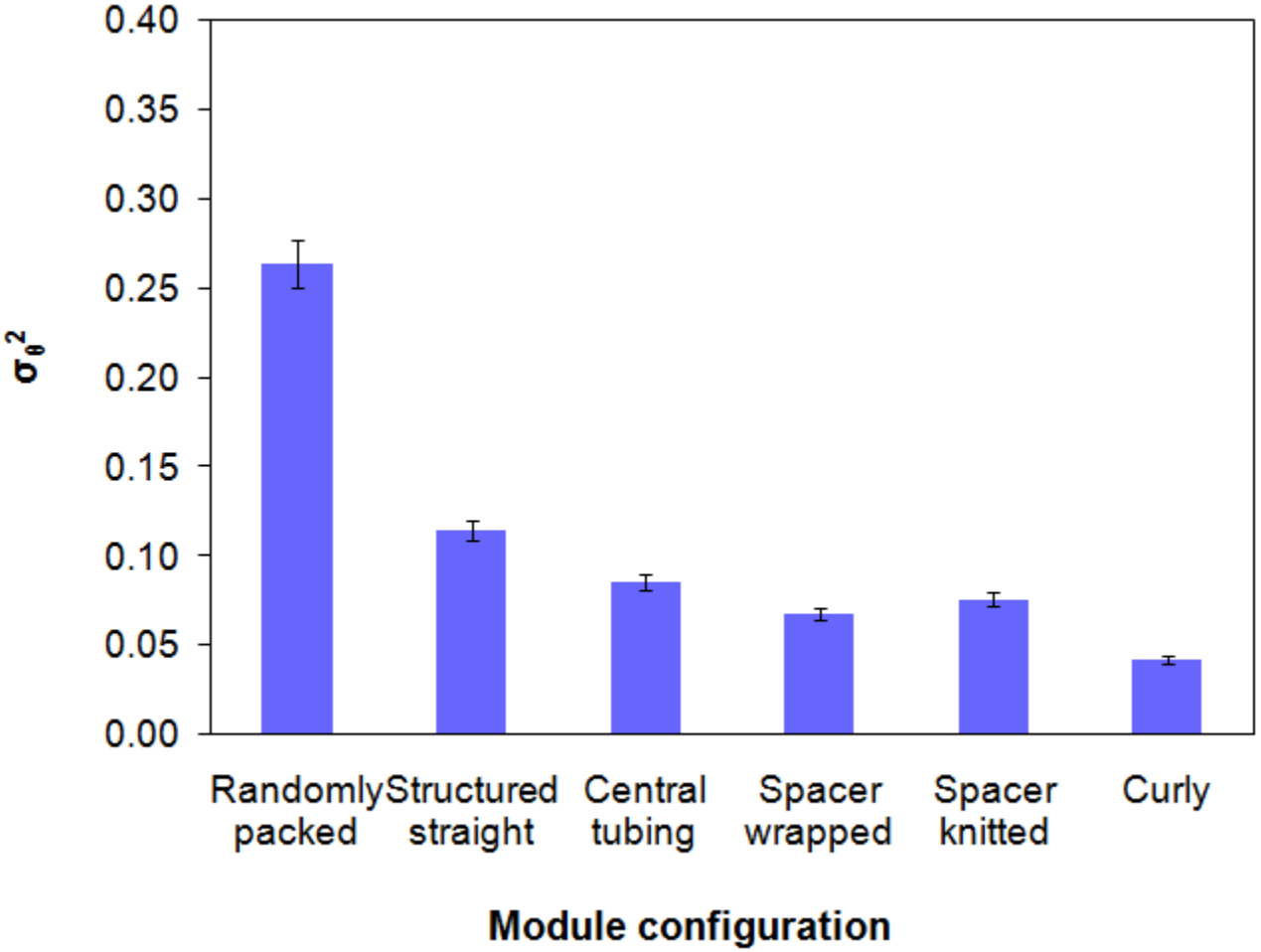


Fig.9. Comparison of variance for various module configurations (Background solution: pure water; tracer: sodium chloride solution, 1mol/L; amount: 1mL; Q_f =2.5 L·min^{-1}, T_f=298 K)

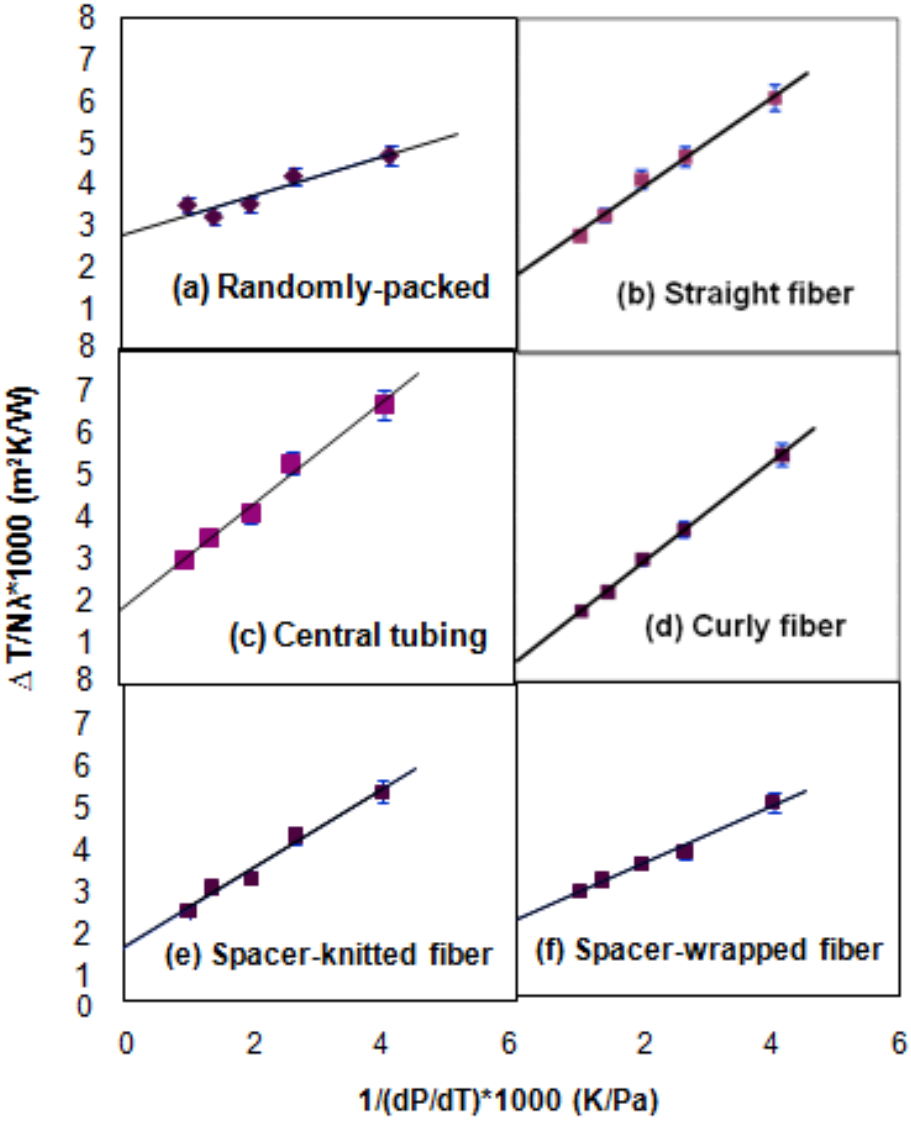


Fig. 10. Relationship between $\frac{\Delta T}{N\gamma}$ vs. $\frac{1}{dP/dT}$

[Q_f =4 L·min^{-1}(Re$_f$=1800), Q_p =0.8 L·min^{-1} (Re$_p$=180), T_m=303~333K]

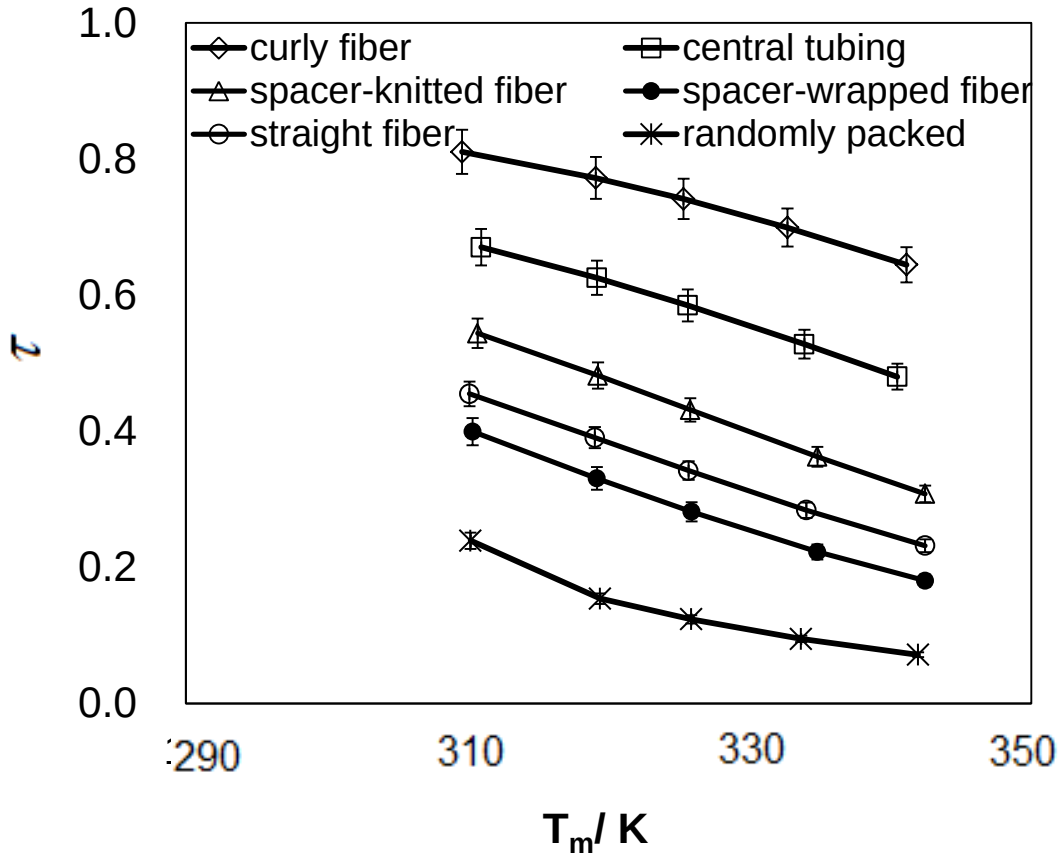


Fig. 11. Comparison of the TP effect for various module configurations in pure water tests [Q_f =4 L·min^{-1}(Re$_f$=1800), Q_p =0.8 L·min^{-1} (Re$_p$=180), T_m=303~333K]

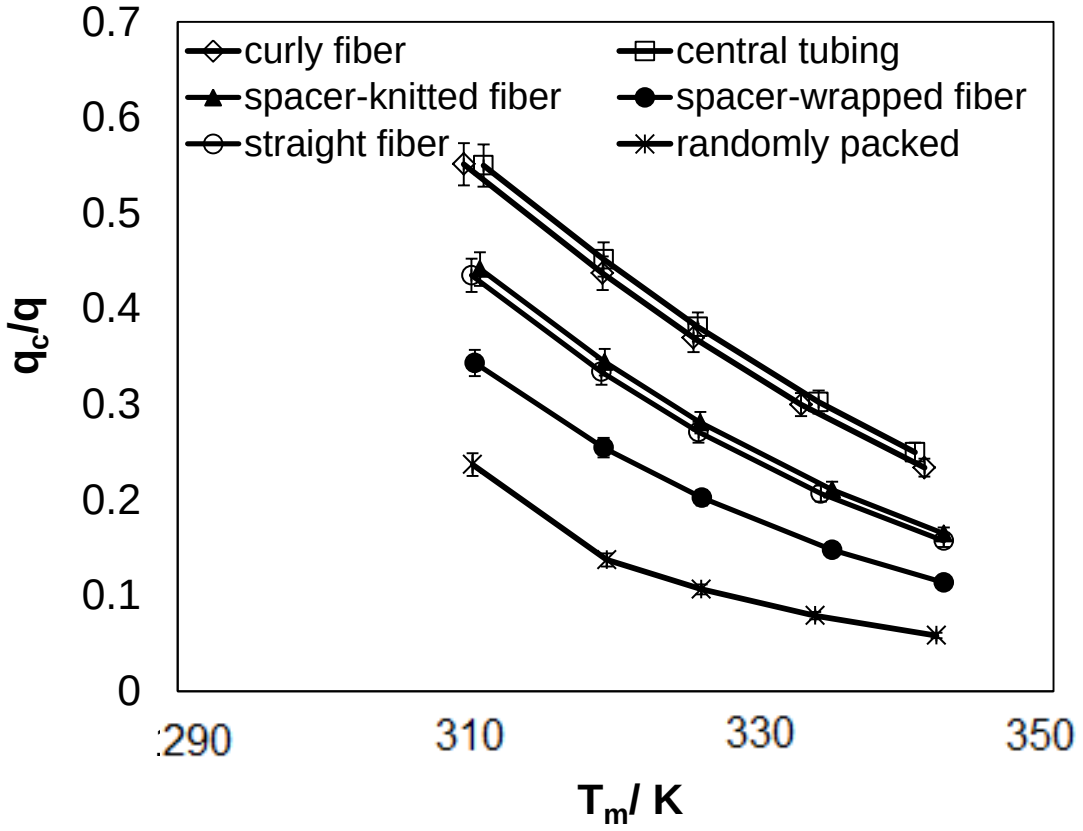


Fig. 12. Heat-loss assessment for various module configurations in pure water tests [Q_f =4 L·min^{-1}(Re$_f$=1800), Q_p =0.8 L·min^{-1} (Re$_p$=180), T_m=303~333K]

Table 1 Module specifications and membrane properties

Module specifications						
Membrane type	Housing diameter, d_s	No of fibers, n	Effective fiber length L, mm	Packing density ϕ, %	Membrane area A, m^2	Remark
PVDF	19 mm	51	450	30	0.1-0.12	The winding angle is taken into account to calculate membrane area of the curly-fiber module
Membrane properties						
Dimension	Pore size (μm)	Contact angle ($^\circ$)	Porosity ε (%)	LEPw (Bar)	Tensile modulus E_t ,MPa	Strain at break δ_b, %
d_o: 1.45 mm δ_m: 235 μm	r_{max}: 0.125 r_{mean}:0.082	106–120	82–85	3.5	42.05	105.4

Table 2 Overall RTD results for various configurations

Configurations	**Mean residence time** t_m**/s**	**Variance** σ_θ^2 **(dimensionless)**
Randomly packed module	7.52	0.263
Structured-straight fiber	7.82	0.115
Central-tubing module	7.93	0.085
Curly-fiber module	8.60	0.041
Spacer-wrapped fiber module	8.37	0.067
Spacer-knitted fiber module	8.63	0.075

Table 3 Overall comparison for various configurations

Configurations	Flux enhancement*, % (T_f=333K, Re_f=936, Re_p=114)	Variance σ_θ^2 (dimensionless)	TPC (T_m=333K)	q_c/q (T_m=333K)
Randomly packed module	--	0.263	0.07	0.07
Structured-straight fiber	180	0.115	0.24	0.16
Central-tubing module	280	0.085	0.49	0.24
Curly-fiber module	301	0.041	0.65	0.22
Spacer-wrapped fiber module	283	0.067	0.19	0.10
Spacer-knitted fiber module	323	0.075	0.33	0.15

* The flux enhancement over the randomly packed module