Analysis of the effect of turbulence promoters in hollow fiber membrane distillation modules by computational fluid dynamic (CFD) simulations

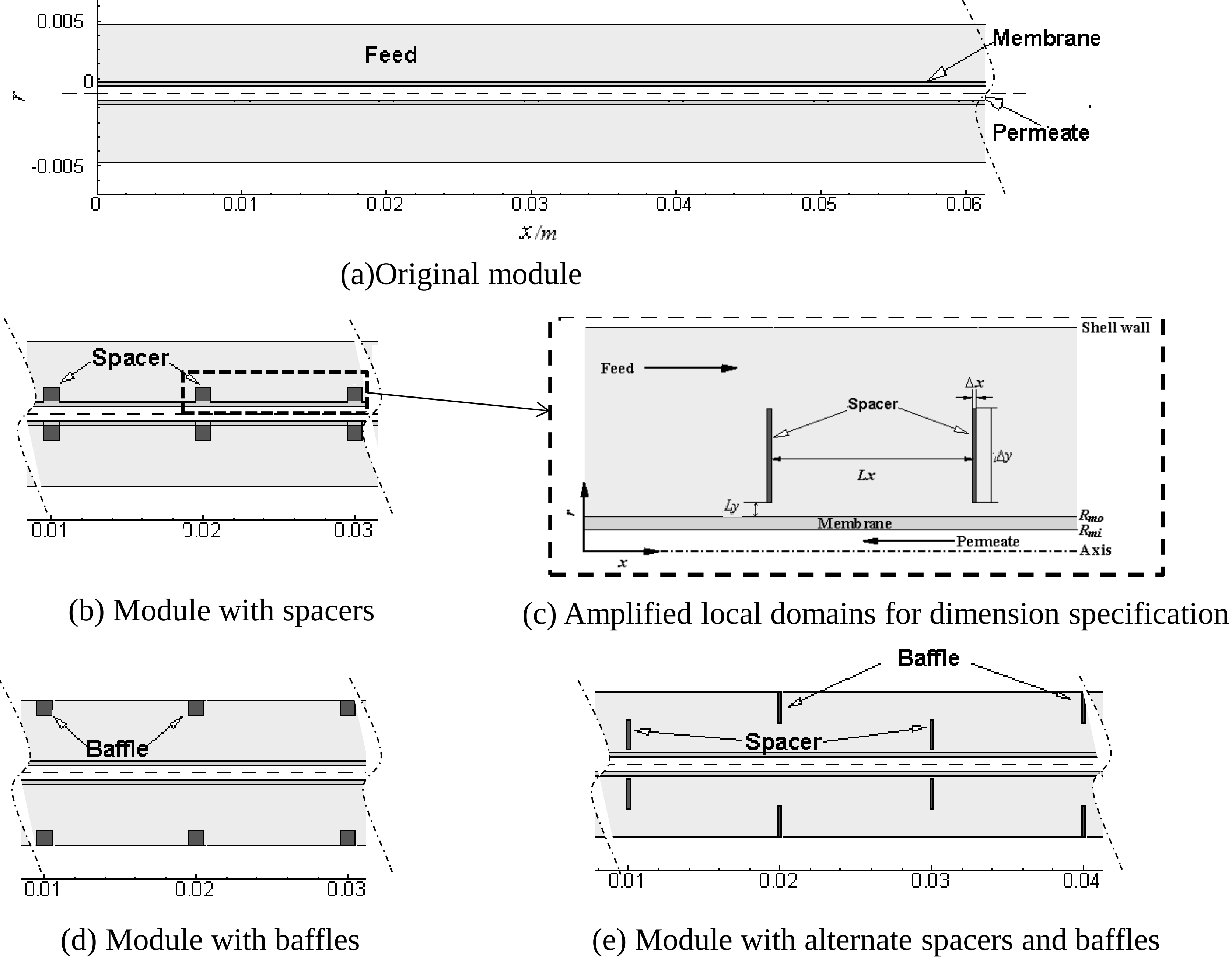
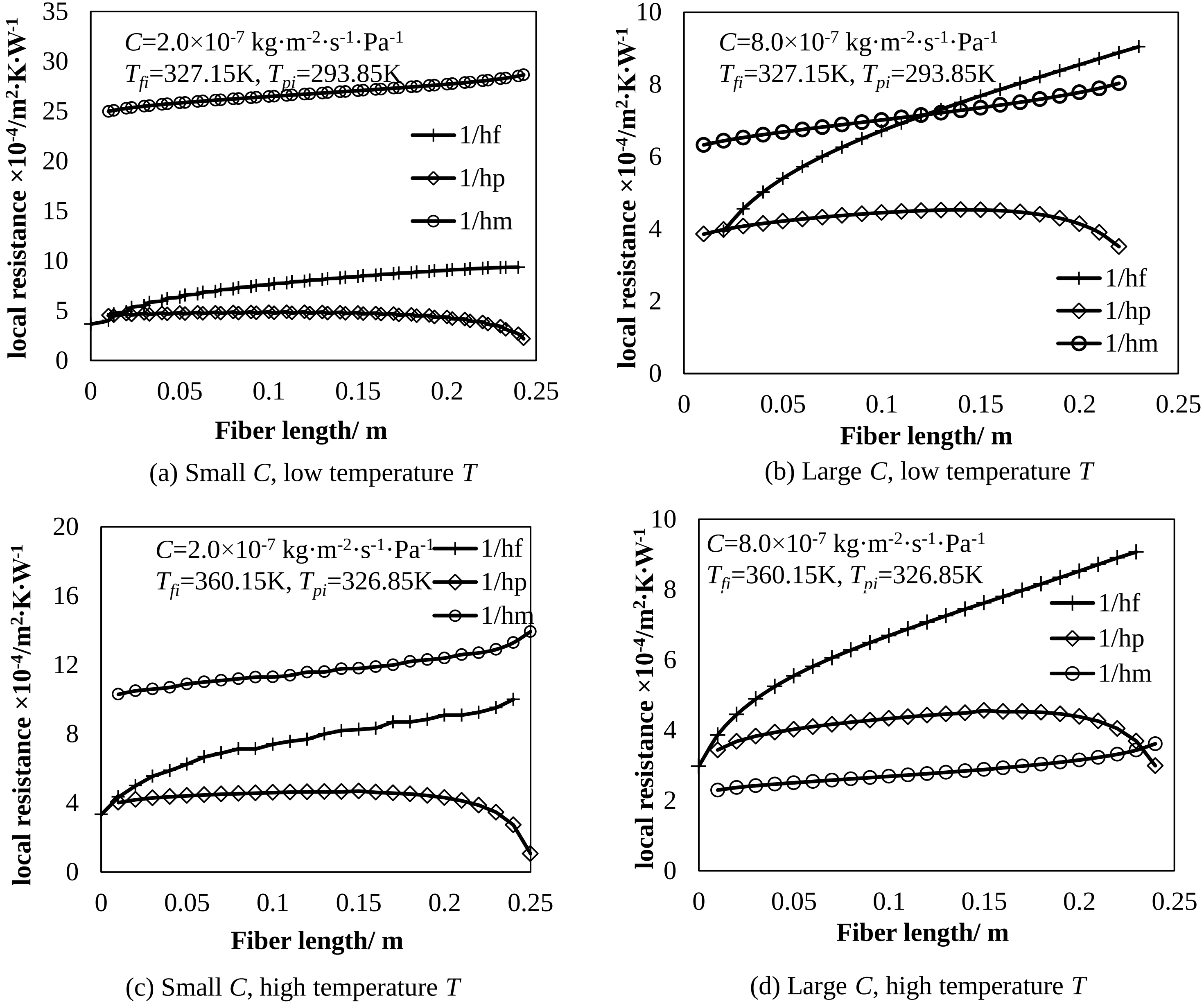


Fig. 1. Schematic of axially-symmetry single fiber modules in CFD simulating domains



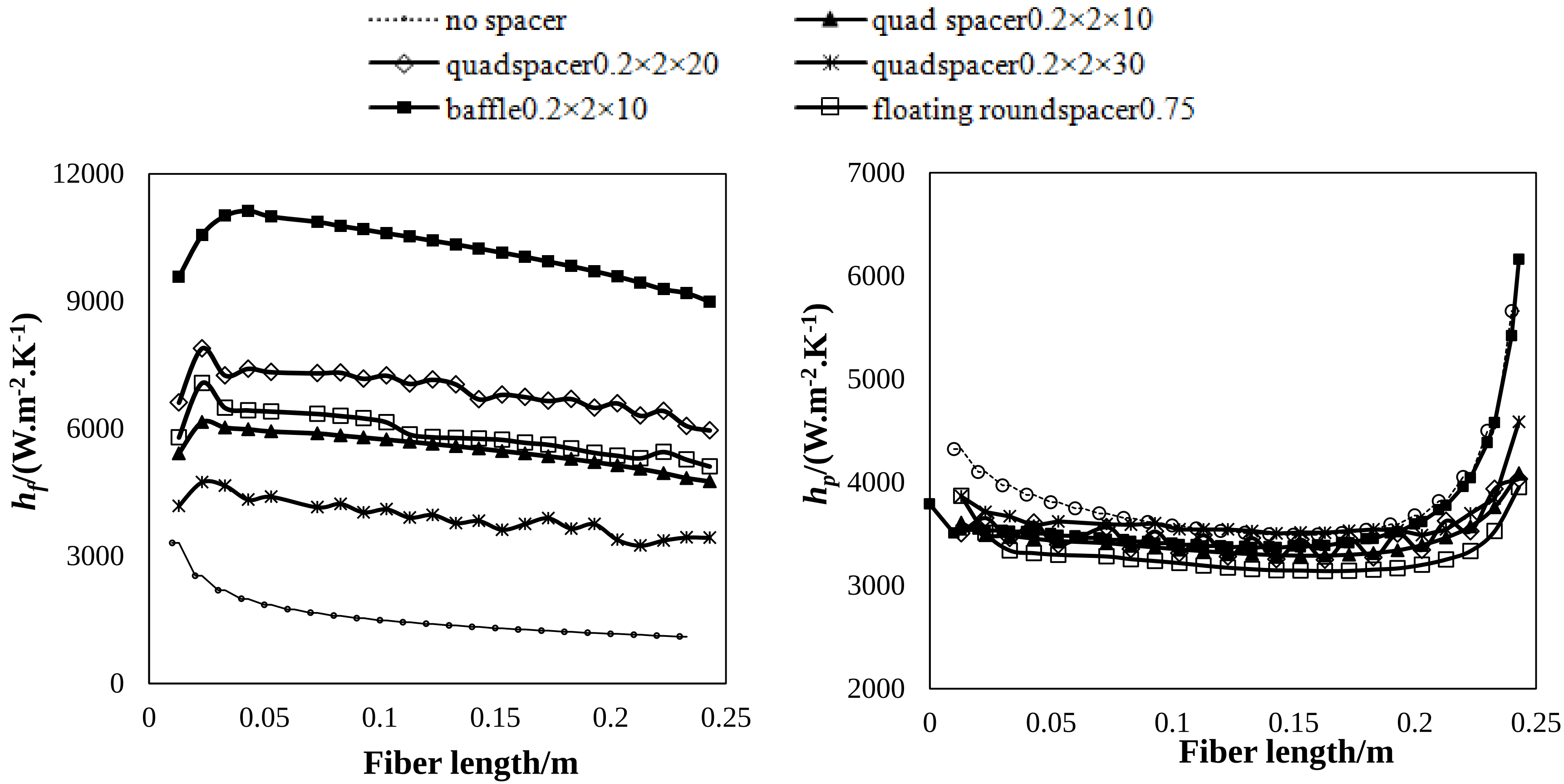
(a) Small C, low temperature T

(b) Large C, low temperature T

(c) Small C, high temperature T

(d) Large C, high temperature T

Fig. 2. Local heat-transfer coefficients distributions along the module length under various operating conditions (T_{fi} = 327.15 &360.15 K, T_{pi} = 293.85 & 326.85 K, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1}, C = 2.0& 8.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1})



(a) h_f distributions vs. module length L

(b) h_p distributions vs. module length L

Fig. 3. h_f &h_p distributions along the fiber length for various turbulence promoters
(C=8.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25m, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1}, T_{fi}= 327.15 K, T_{pi}= 293.85 K)

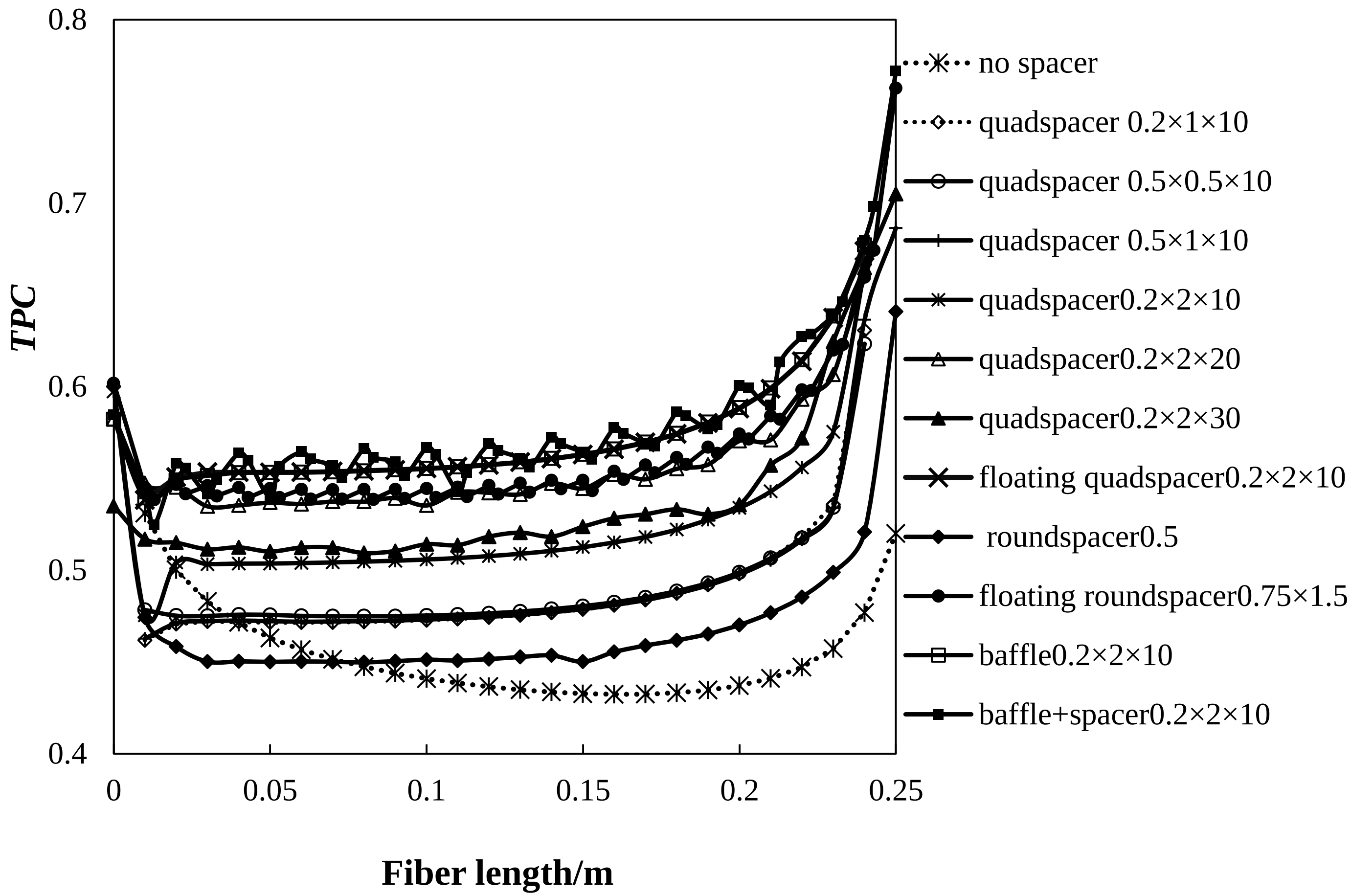


Fig. 4. *TPC* distribution along the fiber length for modules with turbulence aids of various specification (C = 8.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25m, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1}, T_{fi} = 327.15 K, T_{pi} = 293.85 K)

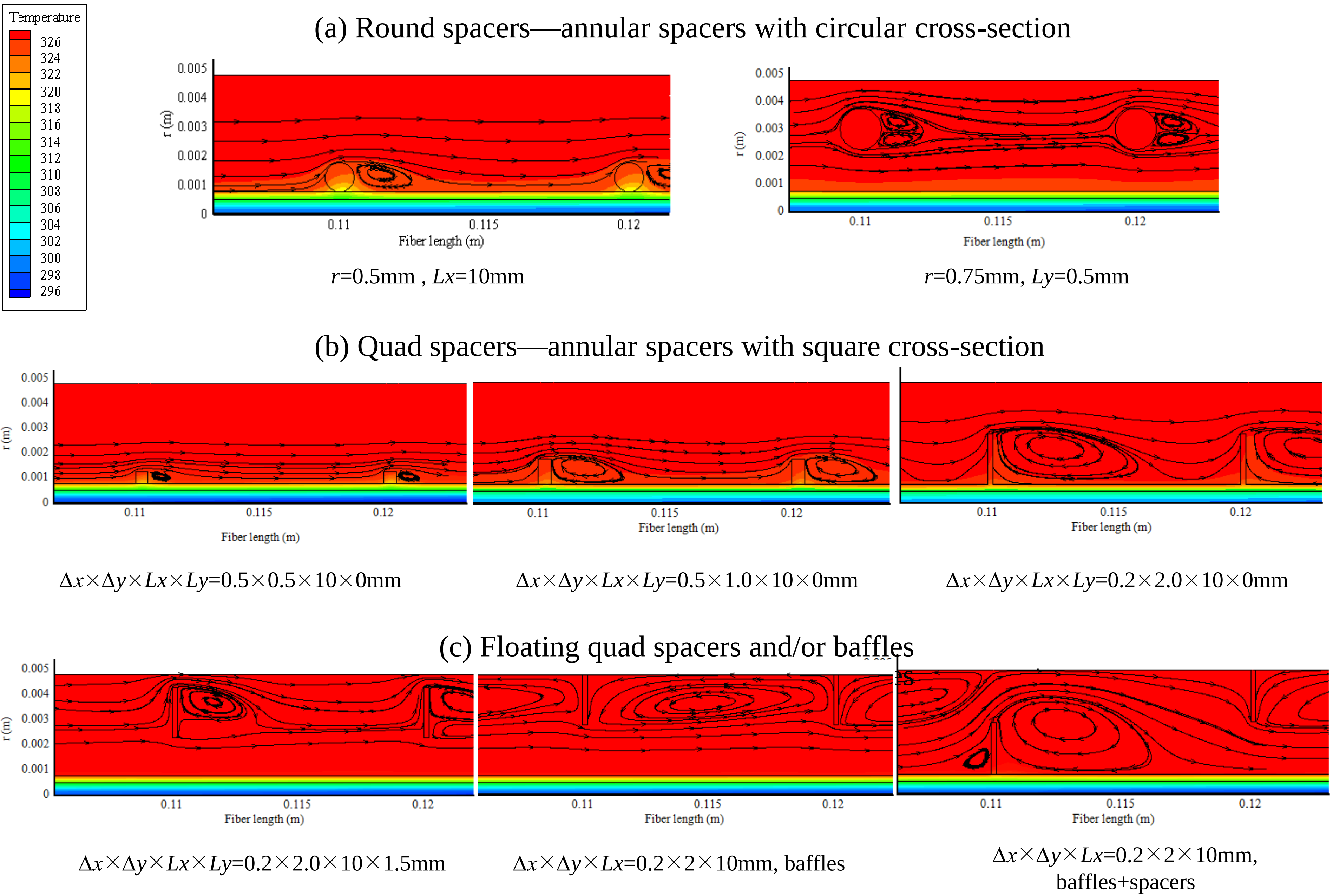


Fig. 5. Local flow field visualization for modules with various turbulence promoters ($C = 8.0\times10^{-7}$ kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25m, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1}, T_{fi}= 327.15 K, T_{pi}= 293.85 K)

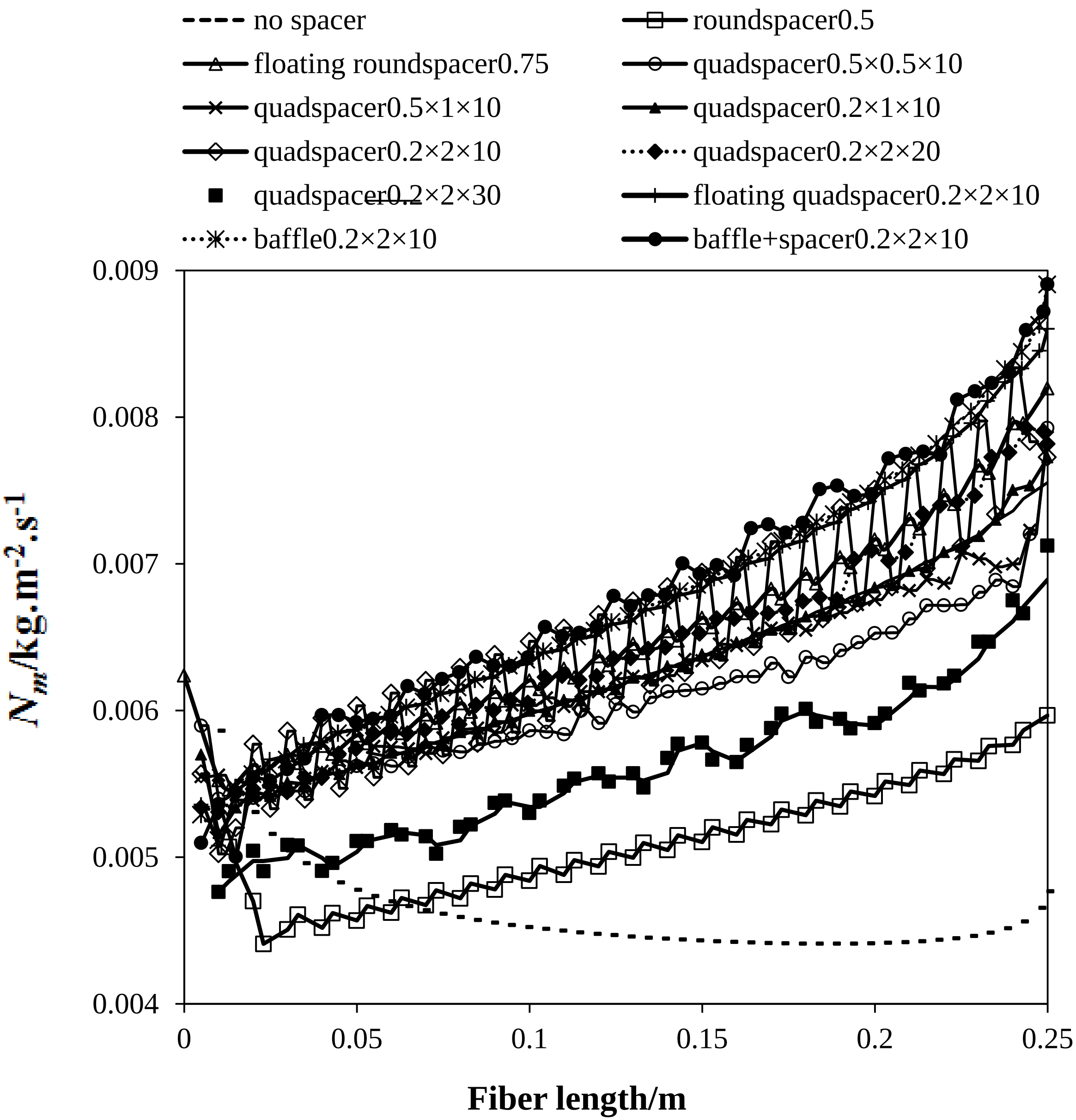


Fig. 6. Mass flux N_m distribution along the fiber length for modules with turbulence aids of various specification (C = 8.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25m, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1}, T_{fi} = 327.15 K, T_{pi} = 293.85 K)

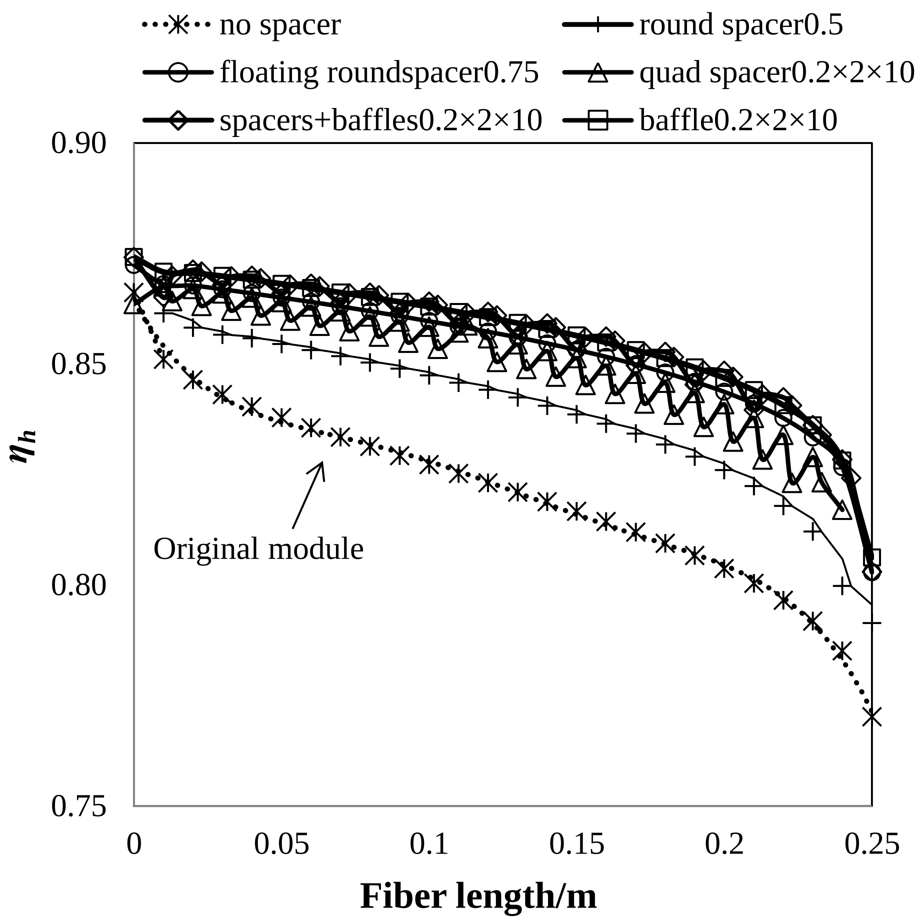


Fig. 7. η_h distribution along the module length for modules with various turbulence promoters (C = 8.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25m, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1}, T_{fi}= 327.15 K, T_{pi}= 293.85 K)

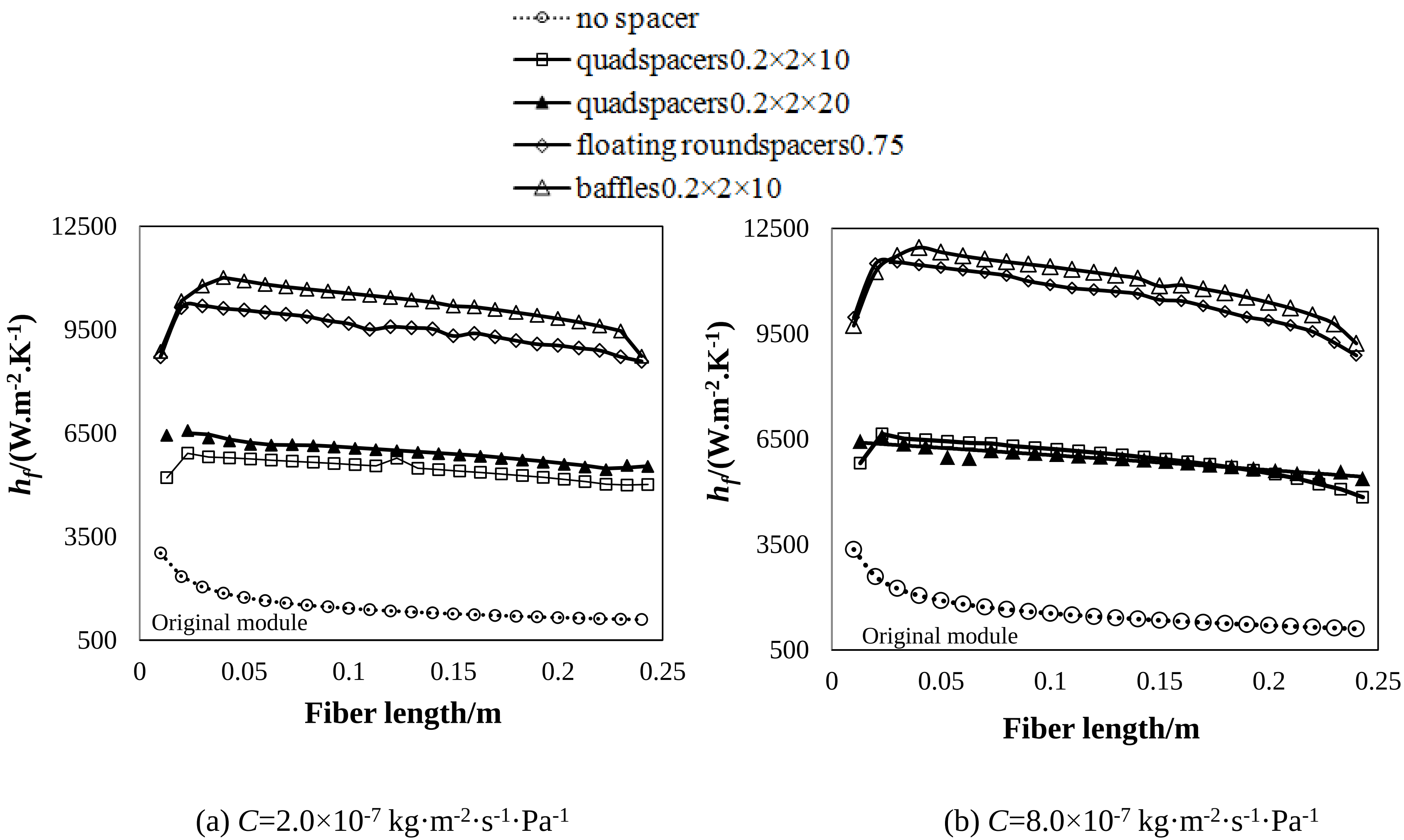
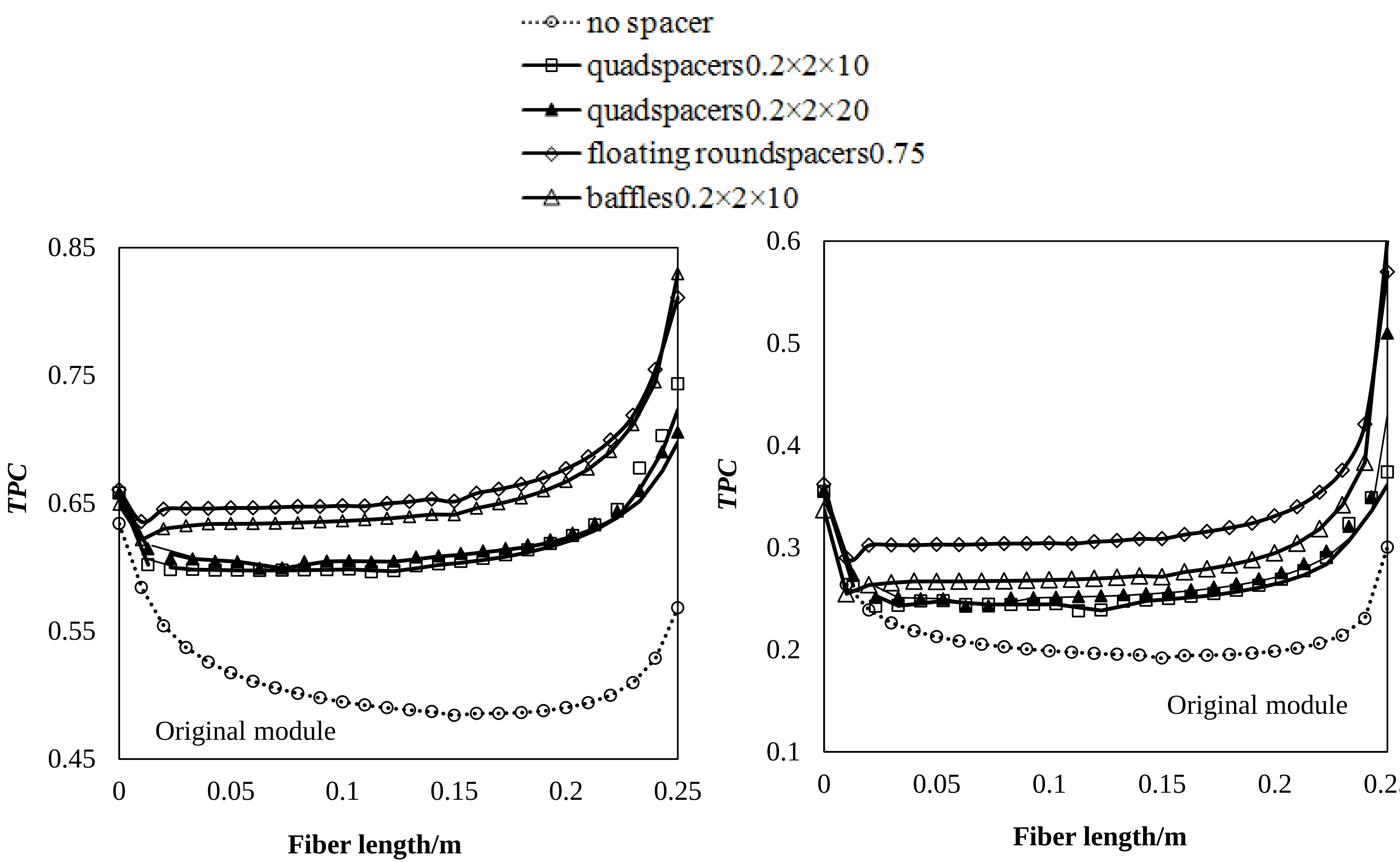


Fig. 8. Effects of turbulence promoters on h_f distributions along the fiber length at high temperatures for membranes with different C values (L=0.25m, T_{fi}= 360.15 K, T_{pi}= 326.85 K, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1})



(a) C=2.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}

(b) C=8.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}

Fig. 9. Effect of turbulence promoters on *TPC* distributions along the fiber length at high temperatures for membranes with different C values (L=0.25m, T_{fi}= 360.15 K, T_{pi}= 326.85 K, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1})

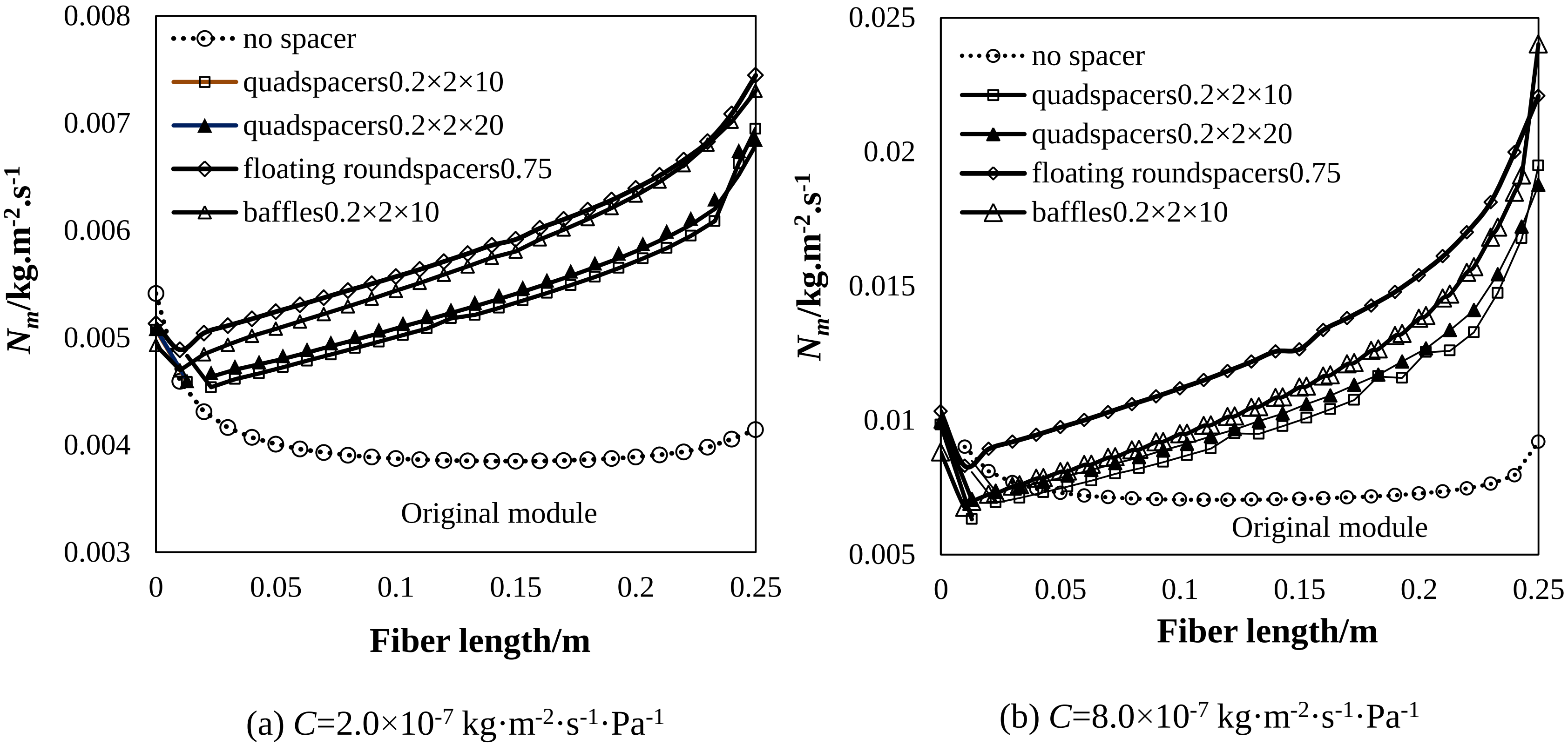
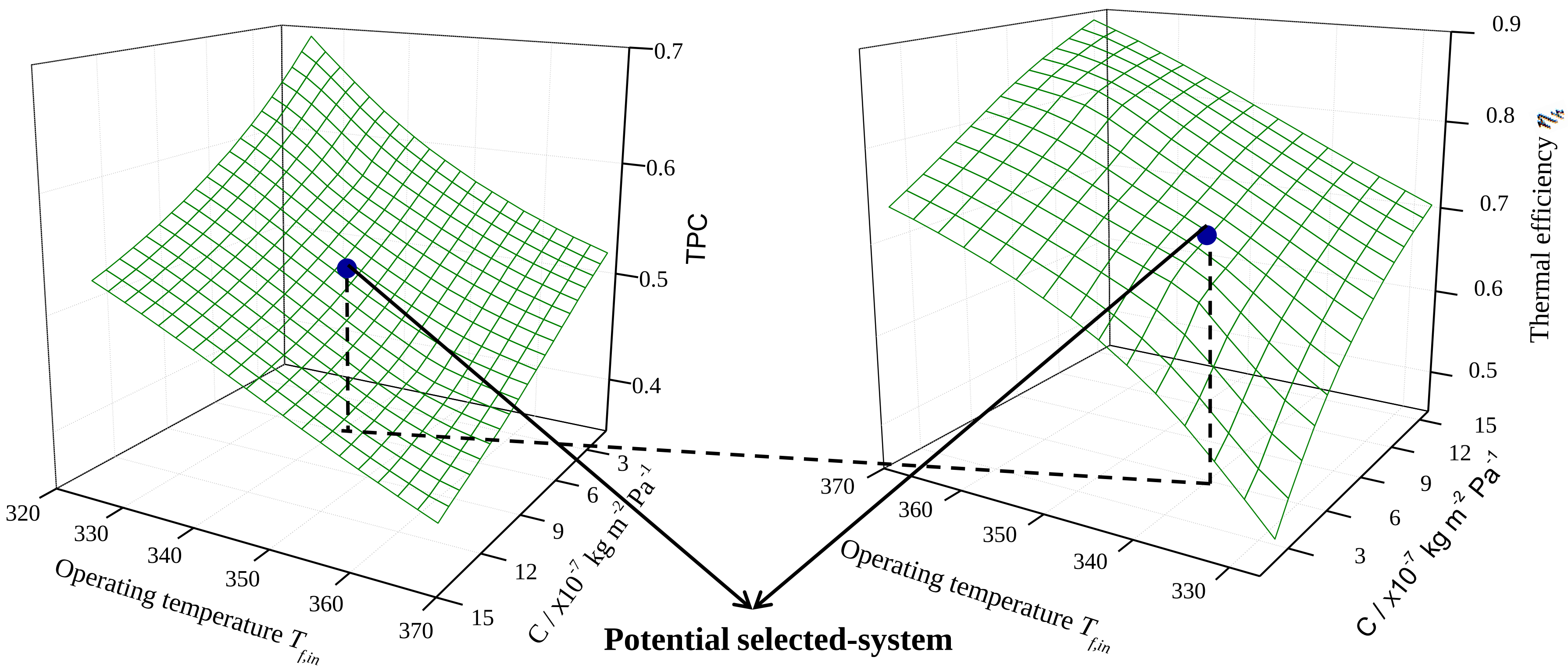


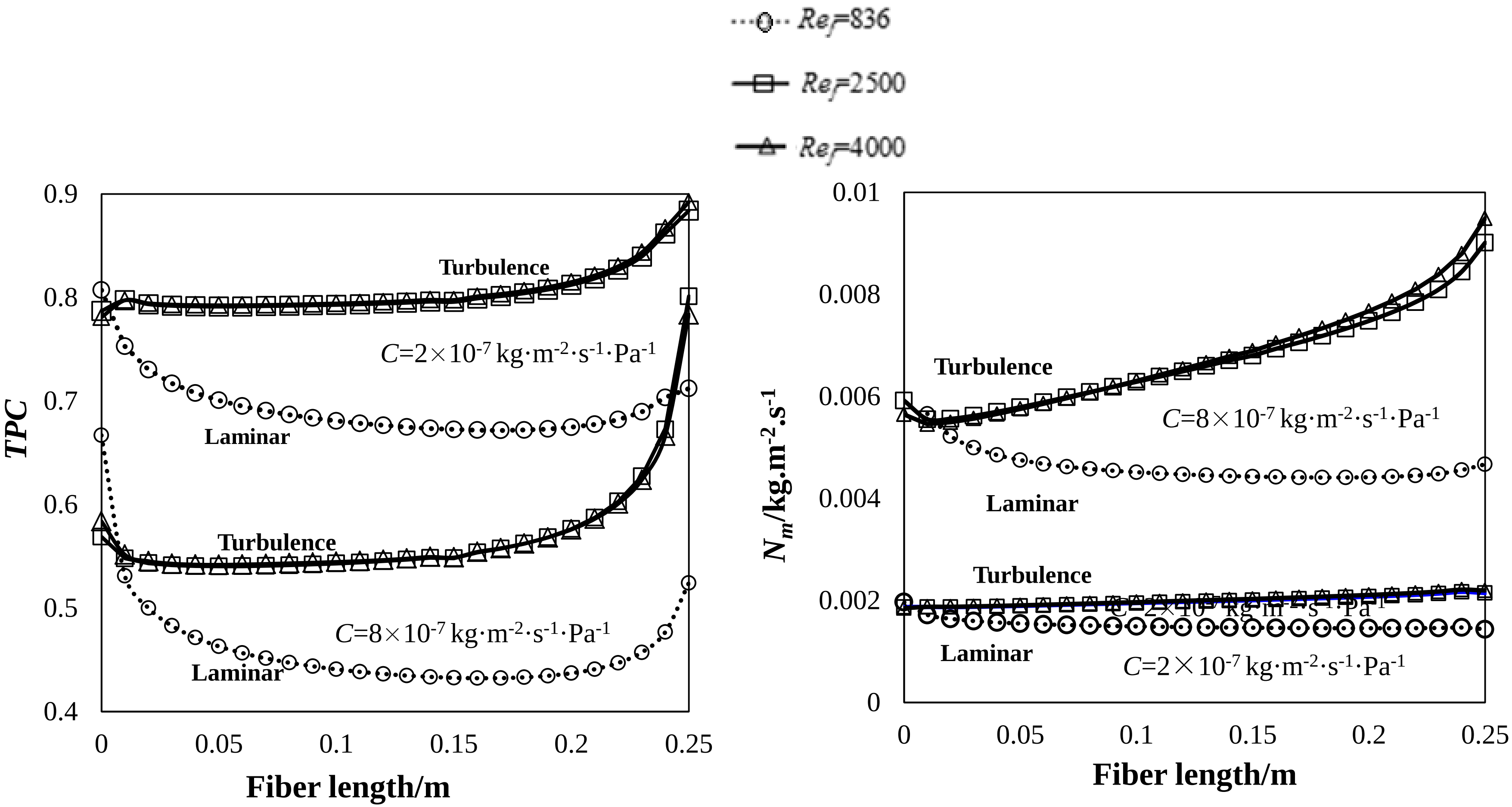
Fig. 10. Effect of turbulence promoters on N_m distributions along the fiber length at high temperatures for membranes with different C values (L=0.25m, T_{fi}= 360.15 K, T_{pi}= 326.85 K, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1})



(a) *C&T* vs. *TPC*

(b) *C&T* vs. η_h

Fig. 11. Effects of *C* values and operating temperatures on the *TPC* and thermal efficiency for the original module (C = 2.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25m, u_{fi}=0.06 m·s^{-1}, u_{pi}=0.417m·s^{-1}, T_{fi}= 327.15 K, T_{pi}= 293.85 K)



(a) *TPC* distributions vs. module length *L*

(b) N_m distributions vs. module length *L*

Fig. 12. Effects of flow velocity on *TPC* and N_m distributions along the fiber length for unaltered modules with different *C* values (C=2 & 8.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, *L*=0.25m, Re_f=836, 2500 & 4000, T_{fi}= 327.15 K, Re_p= 460, T_{pi}= 293.85 K)

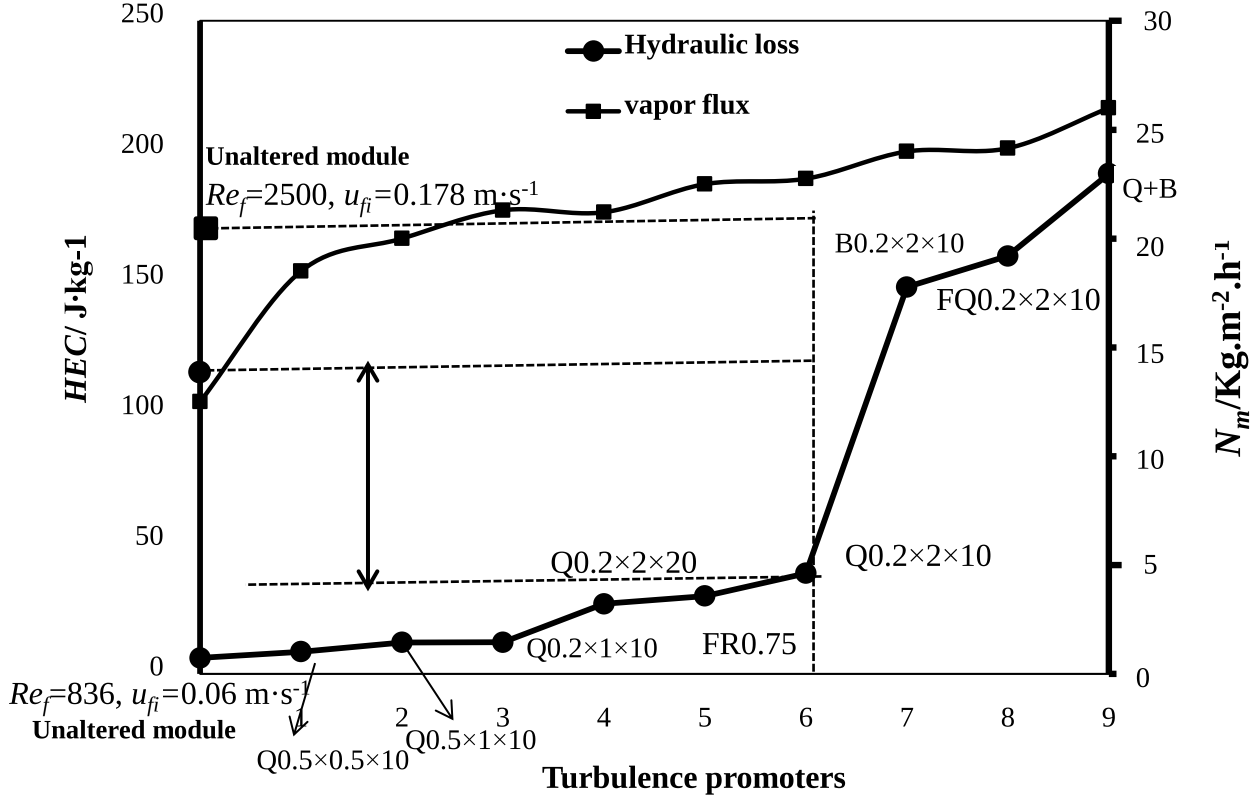


Fig. 13. Hydraulic loss and vapor flux comparisons for various turbulence promoters [C = 8.0$\times$10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25m, u_{fi}=0.06 m·s^{-1} for all modified modules and u_{fi}=0.06 & 0.178 m·s^{-1} for the original module, u_{pi}=0.417m·s^{-1} (Re_p= 460), T_{fi}= 327.0 K, T_{pi}= 294.0 K, Q=quad spacer, FR=floating round spacer, B=baffle, FQ=floating quad spacer, Q+B=quad spacer + baffle]

Table. 1. specification of various turbulence promoters

Insertion type			Spacer				Baffle		
			Δx / mm	Δy / mm	Lx / mm	Ly / mm	Δx / mm	Δy / mm	Lx / mm
1	No spacer	Original	-	-	-	-	-	-	-
2	Round spacer	Attached round spacer 0.5	r=0.5	-	10	-			
3		Floating round spacer 0.75	r=0.75	-	10	0.5			
4	Quad spacer	Quad spacer 0.5×0.5×10	0.5	0.5	10				
5		Quad spacer 0.5×1.0×10	0.5	1.0	10				
6		Quad spacer 0.2×2.0×30	0.2	2.0	30				
7		Quad spacer 0.2×2.0×20	0.2	2.0	20				
8		Quad spacer 0.2×2.0×10	0.2	2.0	10				
9		Floating quad spacer 0.2×2.0×10×1.5	0.2	2.0	10	1.5	-	-	-
10	Baffle	Baffle 0.2×2.0×10	-	-	-	-	0.2	2	10
11		Alternate spacer + baffle 0.2×2.0×10	0.2	2	10		0.2	2	10

Note:

1. quad spacer indicates an annular spacers with quad cross section; while a round spacer means an annular spacer with circular cross section; For instance, a modified module named "quad spacer 0.2×1.0×10" indicates a total number of 24 regularly distanced quad spacers, *Δx* is 0.2 mm, *Δy* is 1.0 mm, the interval *Lx* is 10 mm and *Ly* 0 mm (attached spacer)

2. Δ*x* and Δy are the dimensions of the annular baffle in *x* and *r* directions, respectively; *Lx* is the interval between two spacers or baffles, *Ly* is the vertical gap between the spacers and the membrane outer surface.

Table. 2. Summary of CFD mathematical models, boundary conditions and algorithms

Governing transport equations		
Continuity equation	$\nabla \cdot (\rho \vec{\upsilon}) = 0$	(1)
Momentum transport equation*	$\nabla \cdot (\rho \vec{\upsilon} \vec{\upsilon}) = -\nabla p + \nabla \cdot (\overline{\overline{\tau}}) + \rho \vec{g}$	(2)
Energy conservation equation	$\nabla \cdot (\vec{\upsilon} \rho c_p T) = \nabla \cdot (k \nabla T) + S_h$	(3)
Boundary conditions		
Entrance of fluids (feed/ permeate)**	u_{fi}=0.06 − 0.283 m·s^{-1}, u_{pi}=0.417m·s^{-1}, T_{fi} = 327.15 – 360.15 K, T_{pi} = 294.0 – 327 K	
Exits of fluids (feed/permeate)	outlet pressure is 0.0 Pa (gauge pressure)	
Membrane wall	no-slip condition, conjugate heat conduction: $q_f\big\|_{r=R_{mo}} = q_m\big\|_{r=R_{mo}}$ $q_m\big\|_{r=R_{mi}} = q_p\big\|_{r=R_{mi}}$ $T_f\big\|_{r=R_{mo}} = T_m\big\|_{r=R_{mo}}$ $T_p\big\|_{r=R_{mi}} = T_m\big\|_{r=R_{mi}}$	
Solution algorithms		
Pressure-velocity coupling	SIMPLE (Semi-Implicit Method for Pressure Linked Equations)	
Conservation equation discretization	QUICK (Quadratic Upstream Interpolation for Convective Kinetics)	

*The momentum equation here only involves the motion in fluids, not the penetration through the membrane matrix. no-slip condition and no molecular transport across the membrane is applied in this model;

** typical experimental values

Table. 3. Summary of heat-transfer equations and definitions in MD [32] *

Heat transfer rate Q^{**}	$Q = Q_f = Q_p = Q_{MD} + Q_{HL}$	(4)
Latent heat flux q_{MD}	$q_{MD} = N_m \cdot \Delta H_{T_{fm}} = h_{MD} \cdot \left(T_{fm} - T_{pm}\right) = C \cdot \Delta P$	(5)
Overall heat-transfer coefficient, K [43]	$\frac{1}{K} = \frac{1}{h_f} + \frac{1}{h_m} + \frac{1}{h_p} \cdot \frac{R_{mo}}{R_{mi}}$	(6)
Local heat-transfer coefficient of the feed h_f	$h_f = \frac{q_f}{\left(T_f - T_{fm}\right)}$	(7)
Local heat-transfer coefficient of the permeate h_p	$h_p = \frac{q_p}{\left(T_{pm} - T_p\right)}$	(8)
Equivalent heat-transfer coefficient of the membrane h_m [34]	$h_m = \left(C\Delta P \cdot \Delta H_{T_{fm}} + \frac{k_m}{b}\frac{R_{lm}}{R_{mo}}\right)\frac{1}{\left(T_{fm} - T_{pm}\right)}$	(9)
MD thermal efficiency η_h[33]	$\eta_h = \frac{Q_{MD}}{Q_{MD} + Q_{HL}} = \frac{h_{MD}}{h_{MD} + h_{HL} \cdot \frac{R_{lm}}{R_{mo}}}$	(10)
Temperature-polarization coefficient (TPC) [45]	$TPC = \frac{T_{fm} - T_{pm}}{T_f - T_p}$	(11)
Hydraulic energy consumption (HEC)	$HEC = \frac{\Delta P_{fluid} \cdot V}{N_m \cdot A}$	(12)

*The MD related mass- and heat-transfer equations here only involves in the CFD data postprocessing;

**The heat-transfer rate $Q=q\times A$

Table. 4. Heat-transfer model verification--comparison of experimental data and simulation results (C = 2.0×10^{-7} kg·m^{-2}·s^{-1}·Pa^{-1}, L=0.25 m, T_{fi}=327 K, T_{pi}=294 K)

Temperature verification

Conditions		T_{fi} **(K)**	T_{pi} **(K)**	***Mass flux*** **(kg·m^{-2}·s^{-1})**		**Error (%)**
				Exp.	Sim.	
Original module (u_{pi}=0.417 m·s^{-1})	u_{fi}=0.107m·s^{-1}	327.5	294.1	0.00190	0.00199	4.46
	u_{fi}=0.178m·s^{1}	327.1	293.8	0.00208	0.00201	-3.47
Modified modules (u_{fi}=0.06m·s^{-1}, u_{pi}=0.417m·s^{-1})	Q0.2×2×10	327.2	294.2	0.00211	0.00209	-0.93
	Q0.2×2×30	327.3	294.5	0.00195	0.00189	-2.99

Pressure-drop verification (shell side)

Conditions		**ΔP_f (Pa)**		**Error (%)**
		Exp.	Sim.	
Original module (u_{fi}=0.06m·s^{-1}, u_{pi}=0.417m·s^{-1})		8.1	7.9	-2.46
Modified modules (u_{fi}=0.06m·s^{-1}, u_{pi}=0.417m·s^{-1})	Q0.2×2×10	66.2	66.7	0.65
	Q0.2×2×30	33.5	33.3	-0.58