Gas Separator with the Thermal Transpiration in a Rarefied Gas

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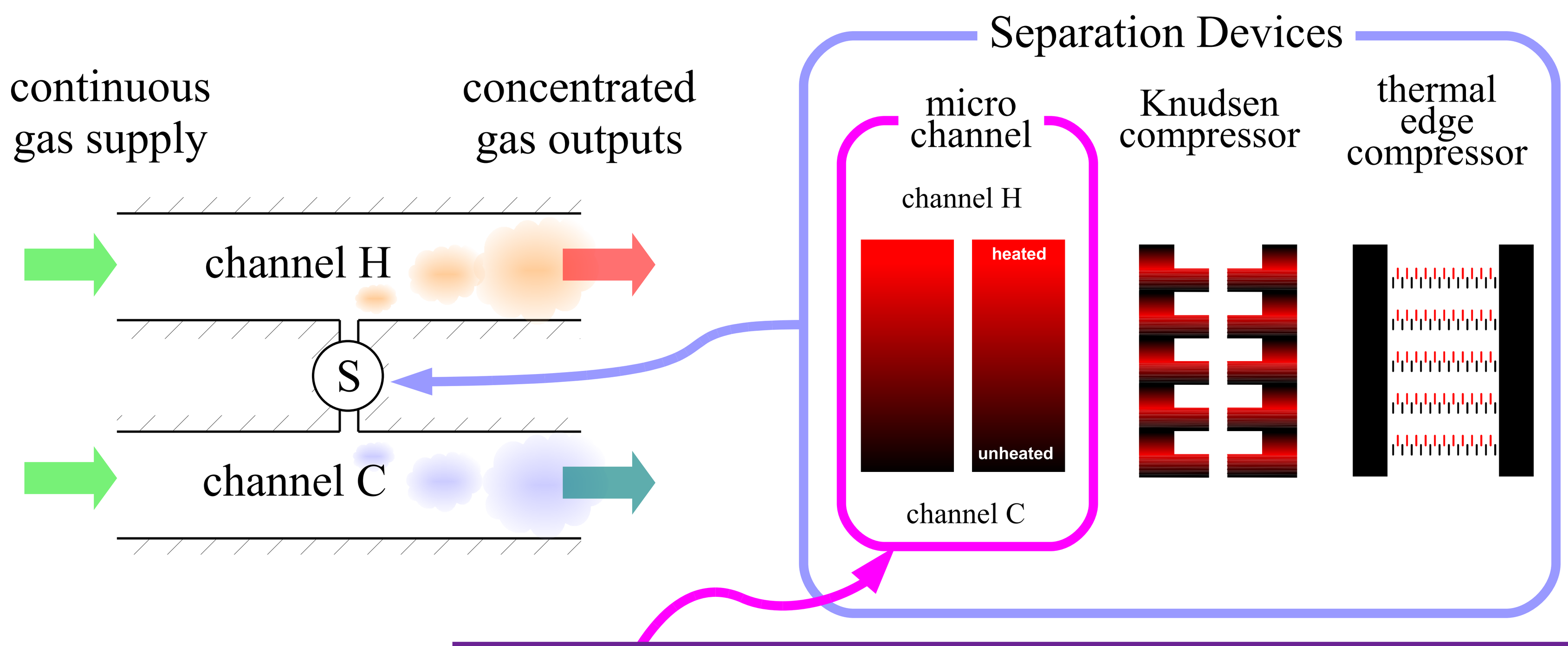
A gas separator that makes use of the thermal transpiration in a rarefied gas is proposed, and its gas separation performance is investigated numerically. The separator consists of two kinds of flow channels with different length scales: An array of micro-channels is used to induce the gas separation effect by the thermal transpiration at intermediate Knudsen number, and two larger channels are used to accumulate the extracted molecules by the gas flows with larger flow velocities. Numerical example shows that the molar fractions of a gas in the two larger channels differ by several percent when the Mach numbers are approximately 0.2 there.

Concept of Gas Separator



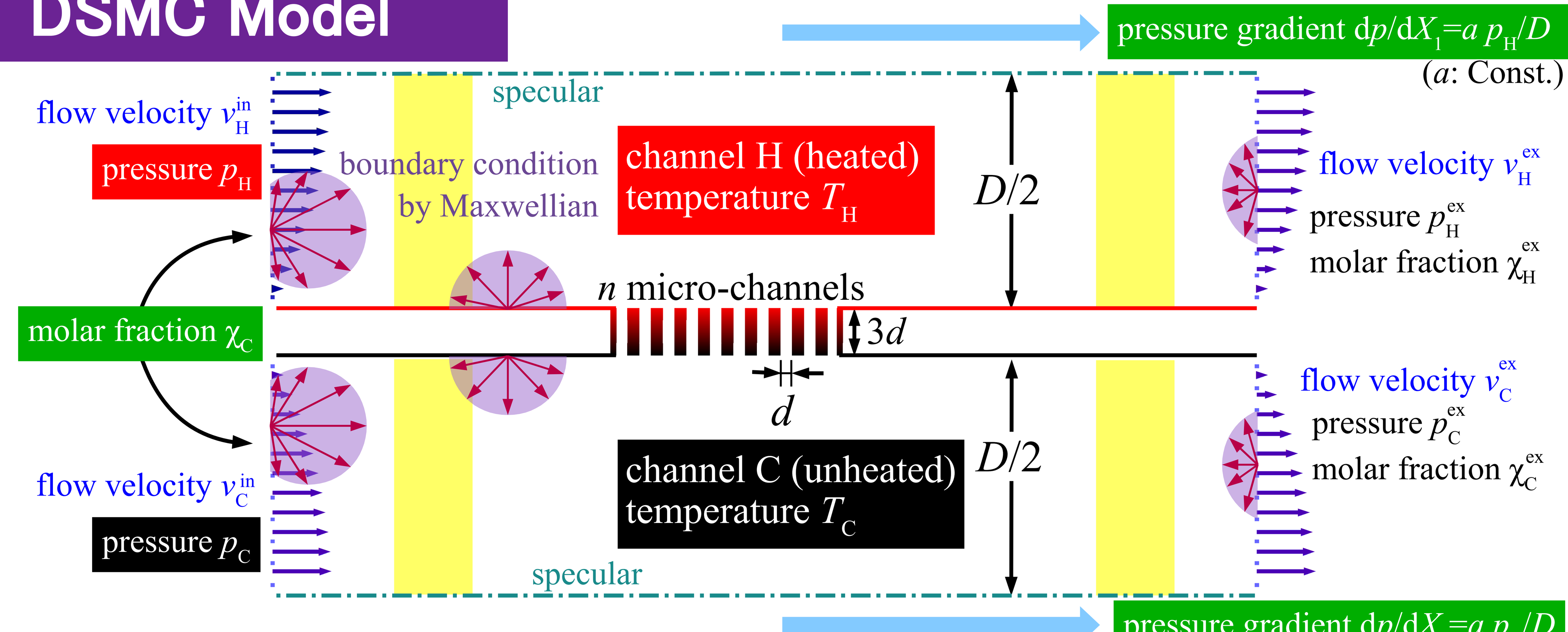
Does it work ?

Conflicting requirements for H and C:

(1) Require **convection effect**
→ width ≫ mean free path ℓ
finite Mach number

(2) Performance of S is limited
→ small width, small flow speed

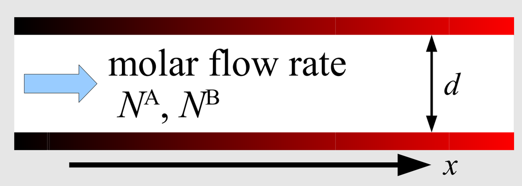
DSMC Model



Velocities v_H^{in}, v_C^{ex}, χ_C^{ex} etc. are determined simultaneously with the DSMC process from the numerical data in regions indicated by [yellow box]

Molecular Exchange Flow by thermal transpiration in a micro-channel

Linear (slow, non-convective) flow in a micro-channel



hard-sphere molecules
m^α: mass, d_m^α: diameter (α = A, B)
$\chi = n^A/n$: molar fraction
T_C, p_C, χ_C: reference state

$$N^\alpha = n_C d(2\kappa T_C/m^A)^{1/2}\left[N_T^\alpha\left(\frac{d}{T_C}\frac{dT}{dx}\right)+N_P^\alpha\left(\frac{d}{p_C}\frac{dp}{dx}\right)+N_\chi^\alpha\left(d\frac{d\chi}{dx}\right)\right]$$

(cf. Database by Kosuge, Takata, *Eur. J. B/Fluids*, 2008)

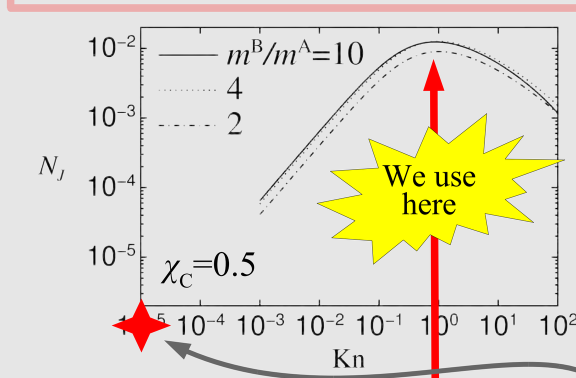
molecular exchange: $N = N^A = -N^B$

$$\frac{d}{p_C}\frac{dp}{dx} = -\frac{N_T^A+N_T^B}{N_P^A+N_P^B}\left(\frac{d}{T_C}\frac{dT}{dx}\right)-\frac{N_\chi^A+N_\chi^B}{N_P^A+N_P^B}\left(d\frac{d\chi}{dx}\right)$$

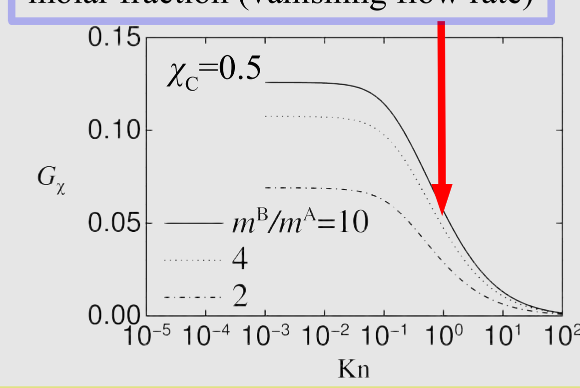
$$\hat{N} = \frac{N}{n_C d(2\kappa T_C/m^A)^{1/2}} = N_J\left(\frac{d}{T_C}\frac{dT}{dx}-\frac{d}{G_\chi}\frac{d\chi}{dx}\right)$$

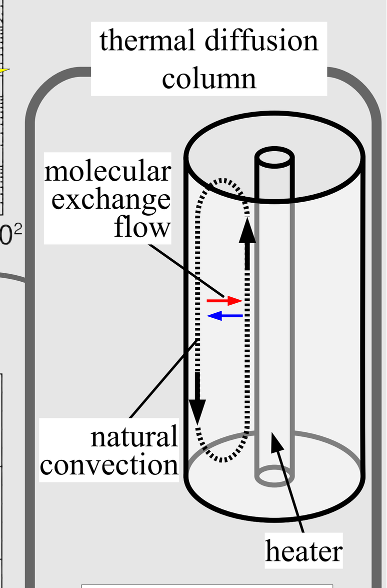
$$N_J = \frac{R_P-R_T}{1+R_P}N_T^A,\quad G_\chi = -\frac{R_P-R_T}{R_P-R_\chi}\frac{N_T^A}{N_\chi^A},\quad R_* = \frac{N_*^B}{N_*^A}.$$

molar flow rate (uniform molar faction)



molar fraction (vanishing flow rate)



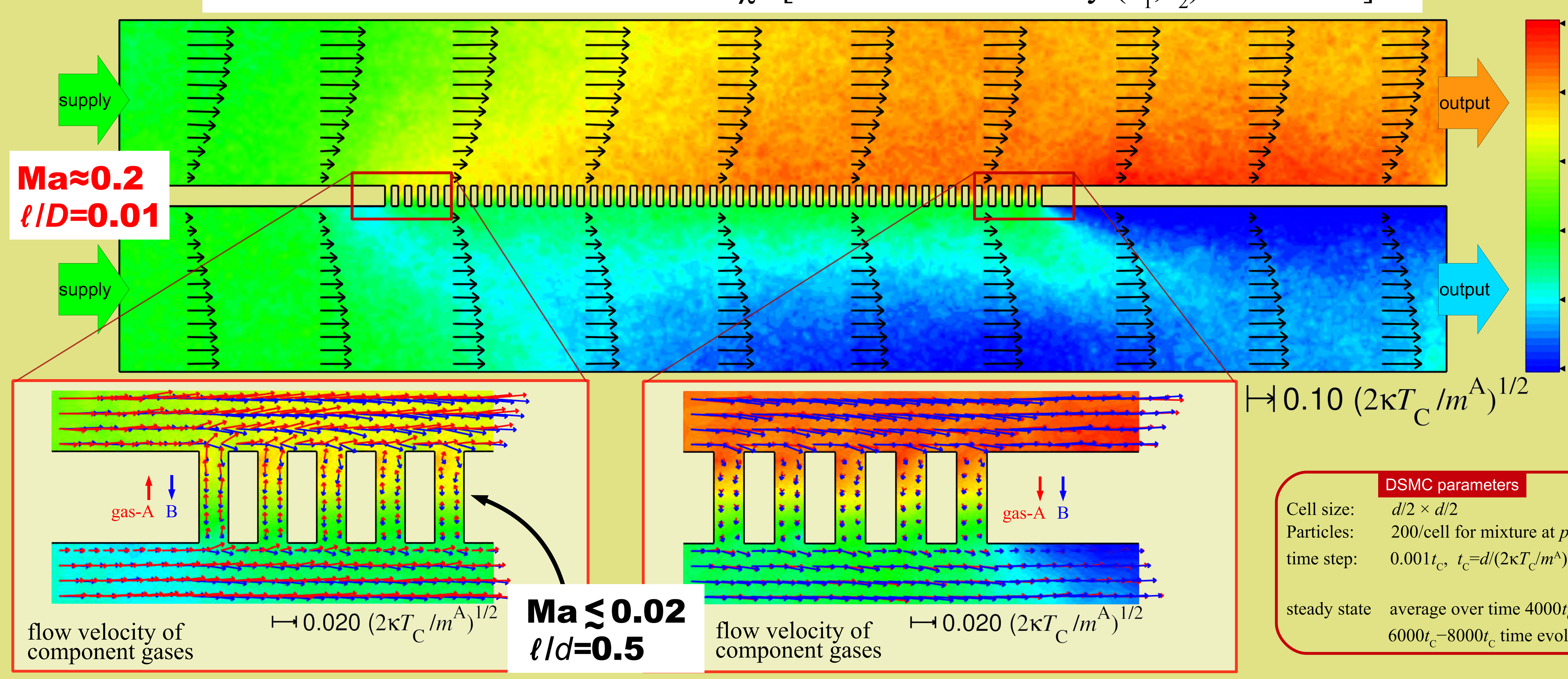


Natural convection is limited to small Kn

DSMC Results

hardsphere, m^B/m^A=10, d_m^B/d_m^A=1, χ_C=0.5, T_H/T_C=3, p_H/p_C=1.3, Kn=ℓ/d=0.5, 50 micro-channels
dp/dX=0.04 p_*/D (*=H, C)

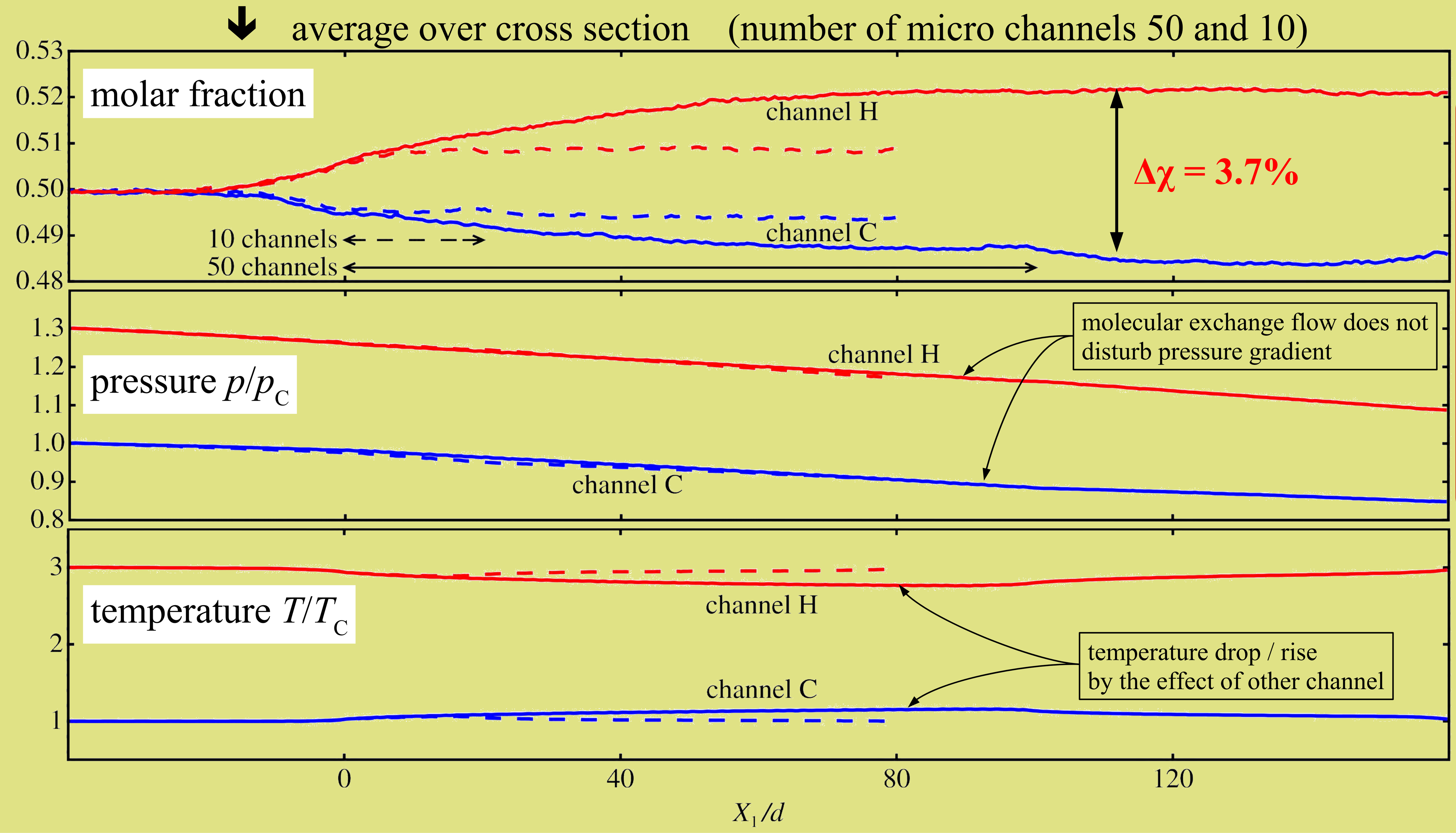
molar fraction of smaller molecules χ [arrows: flow velocity (v_1,v_2) of mixture]



DSMC parameters

Cell size:	$d/2 \times d/2$
Particles:	200/cell for mixture at p_C, T_C
time step:	$0.001t_c$, $t_c=d/(2\kappa T_C/m^A)^{1/2}$
steady state	average over time $4000t_c$ after $6000t_c$–$8000t_c$ time evolution

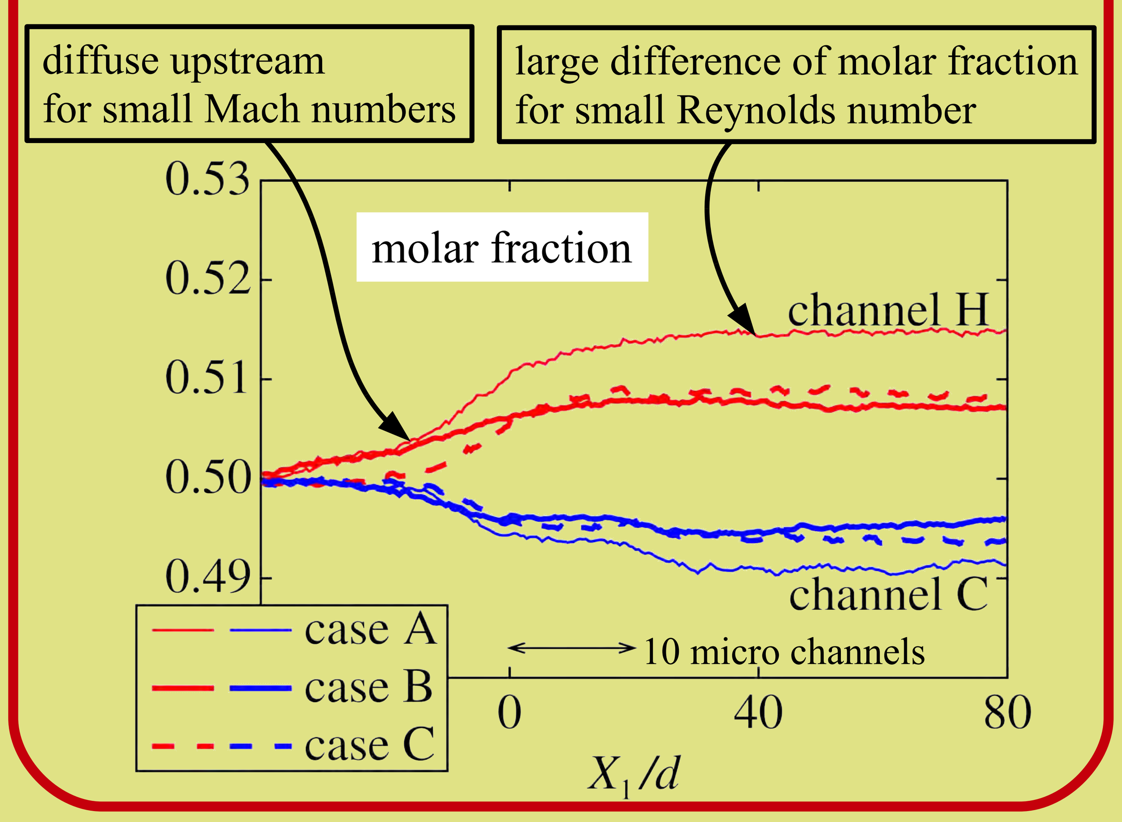
↓ average over cross section (number of micro channels 50 and 10)



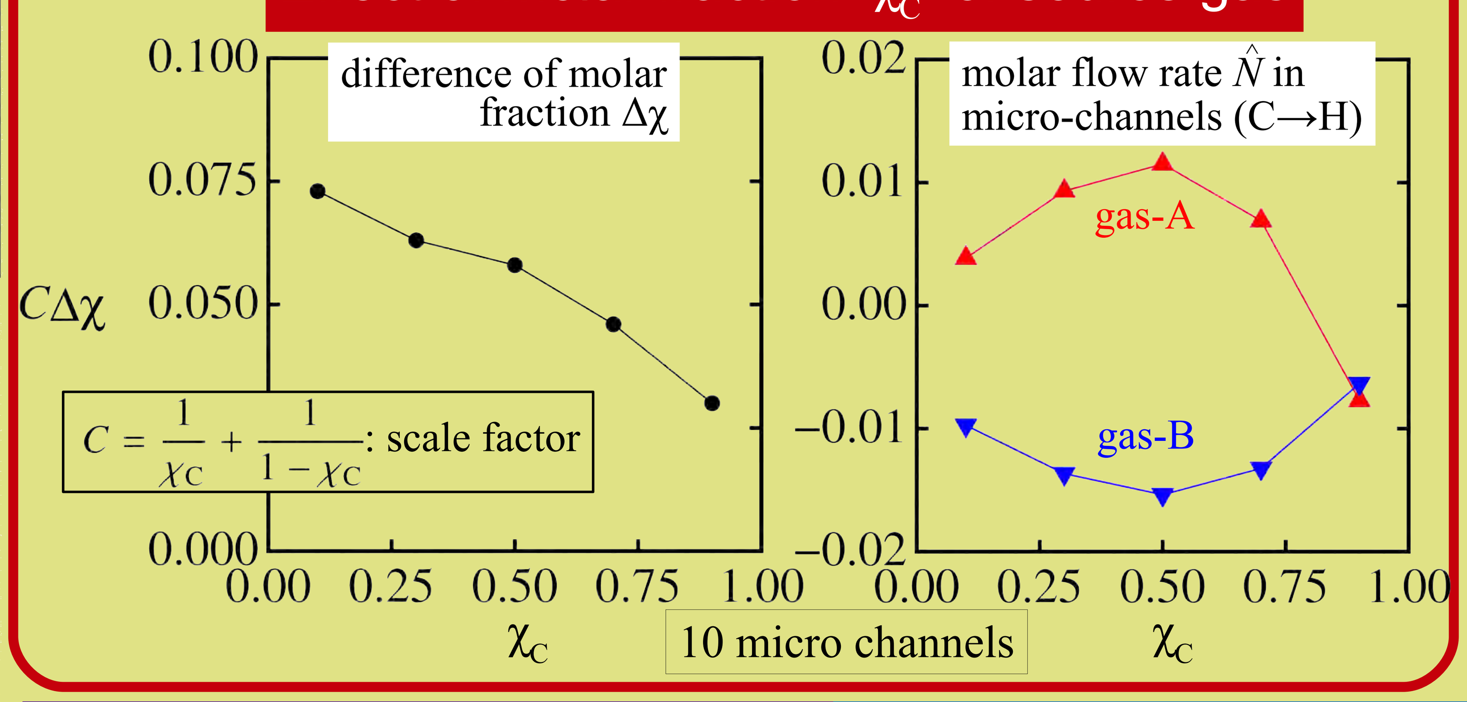
Convection vs Diffusion

Effect of Mach number & Reynolds number

ratio of	case A	:	case B	:	case C
dp/dX	4	:	1	:	8
width D	1	:	2	:	1
Knudsen number Kn$_*$=ℓ/D	2	:	1	:	2
Mach number Ma	~ 1	:	~ 1	:	~ 2
Reynolds number Re=Ma/Kn	~ 1	:	~ 2	:	~ 2
molar flow rate	~ 1	:	~ 2	:	~ 2



Effect of molar fraction χ_C of source gas



Plans for the future

Increase the difference of molar fraction between the exits by

1. Use of thermally-driven pumps
2. Use of the main flows in the opposite direction as in the gas separation by thermal diffusion column

Thank you!

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