Gas and Steam Permeation Properties of Cation-Exchanged ZSM-5 Membrane

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Supplementary Materials

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1. Permeation and separation tests

Figure S1 shows a schematic diagram of the gas permeation test apparatus. Flow rates of the feed and sweep gas in the unary gas permeation test are listed in **Table S1**. The permeated gases were collected by sweeping gas. Nitrogen was used for the H_2 permeation test. And, H_2 was used for the N_2 and SF_6 permeation tests.

In the binary H_2O/H_2 permeation tests, total flow rate of the feed stream was 200 cm^3(STP)/min. To control H_2O partial pressure in the feed stream, flow rate of H_2 with and without the saturator was adjusted. Nitrogen was used as the sweep gas, and its flow rate was 300 or 400 cm^3(STP)/min.

In each permeation test, the permeated gases were analyzed using a gas chromatograph equipped with a TCD detector (GC-8A, Shimadzu, Kyoto, Japan). Molar ratio of the permeated gas and the sweep gas was determined by standard curves. The permeance, Π [mol $m^{-2}s^{-1}Pa^{-1}$] was calculated by the following equation

$$\Pi = u\, r\, A^{-1}\, \Delta p^{-1}$$

where u is flow rate of the sweep gas [mol s^{-1}], r is molar ratio of the permeated gas and the sweep gas [-], A is effective of membrane area, and Δp is partial pressure difference in the feed and permeated side [Pa]. In this study, detection limit is 2×10^{-11} mol $m^{-2}s^{-1}Pa^{-1}$.

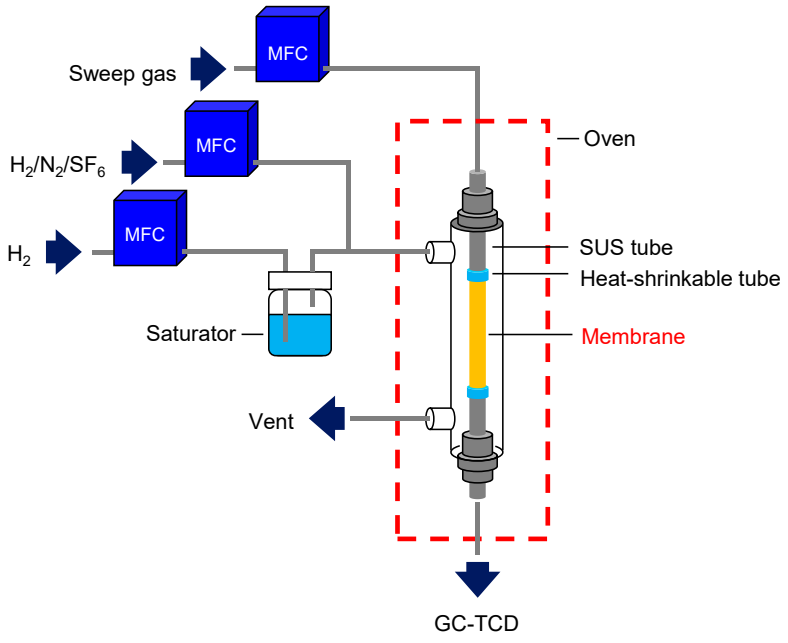


Figure S1. Schematic of the gas permeation test apparatus.

Table S1 Gas flow rate in the unary gas permeation test.

Measurement gas	Flow rate [cm^3(STP)/min]	
	Feed gas	Sweep gas
H_2	200	400
N_2	200	100
SF_6	100	20

2. XRD patterns of powder samples

Figure S2 shows XRD patterns of ZSM-5 powder samples.

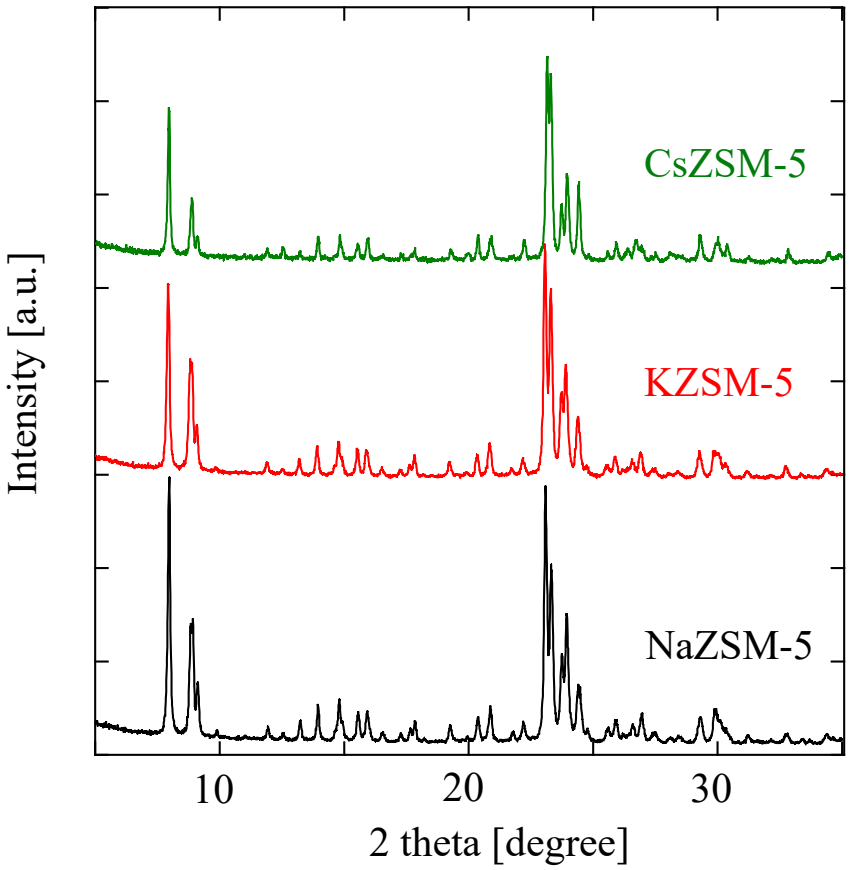


Figure S2. XRD patterns of ZSM-5 powder samples.

3. FE-SEM image and EDS spectra of membranes

Figure S3 shows cross-sectional FE-SEM image and EDS spectra of the ZSM-5 membranes.

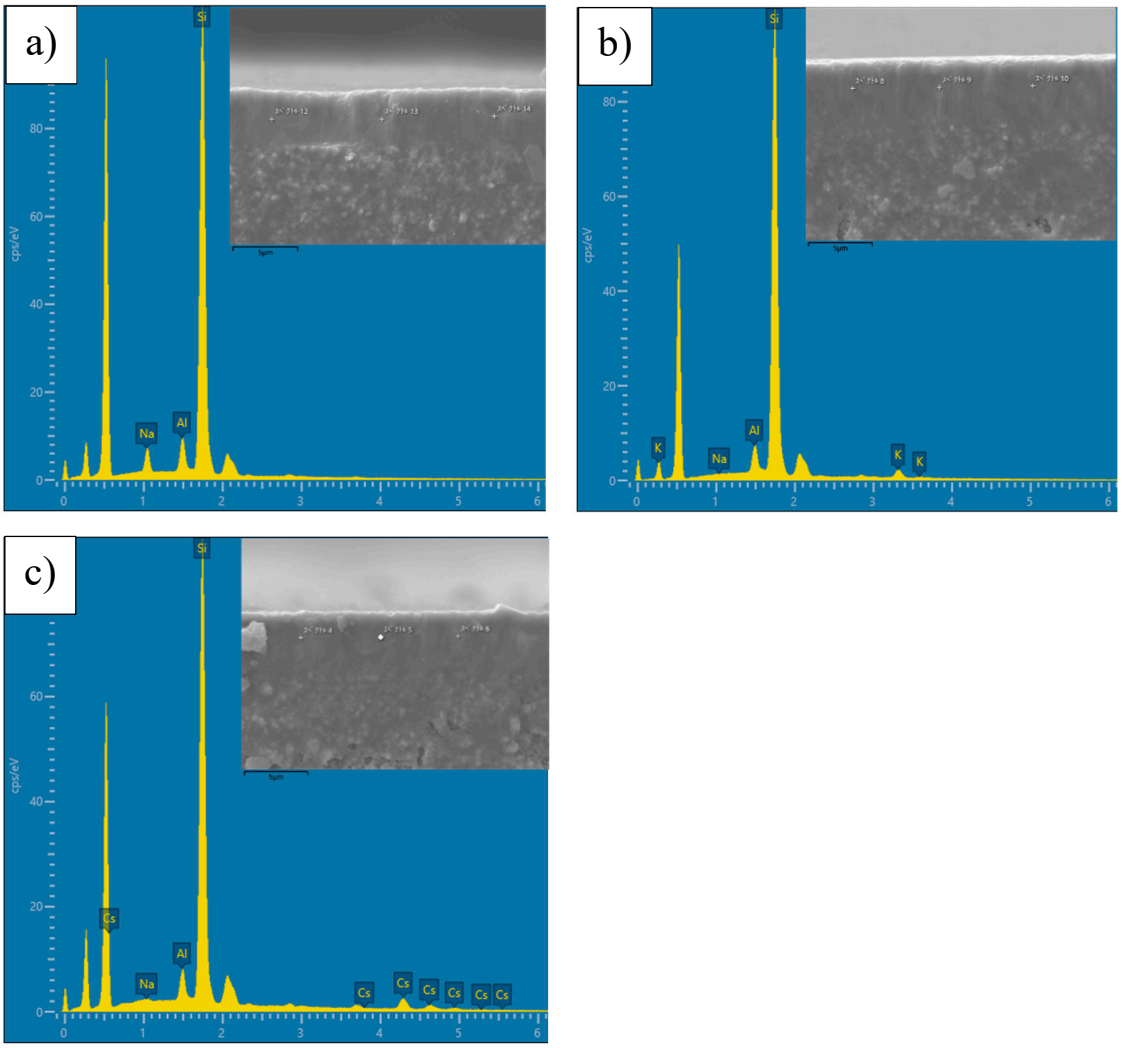


Figure S3. Cross-sectional FE-SEM images and EDS spectra of (a) NaZSM-5, (b) KZSM-5 and (c) CsZSM-5 membranes.

4. Steam adsorption isotherm

Figure S4 shows the isotherms measured at 323 and 343 K.

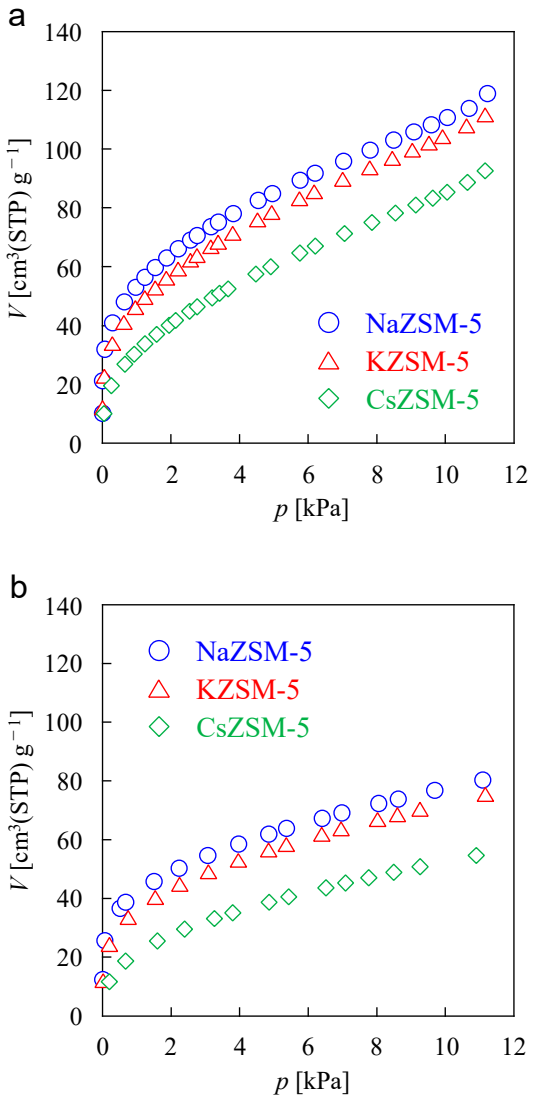


Figure S4. Steam adsorption isotherm of the ZSM-5 powder samples at (a) 323 and (b) 343 K.

5. $p\ V^{-1}$ vs p plot

Figure S5 shows the $p\ V^{-1}$ vs p plot at 323 and 343 K.

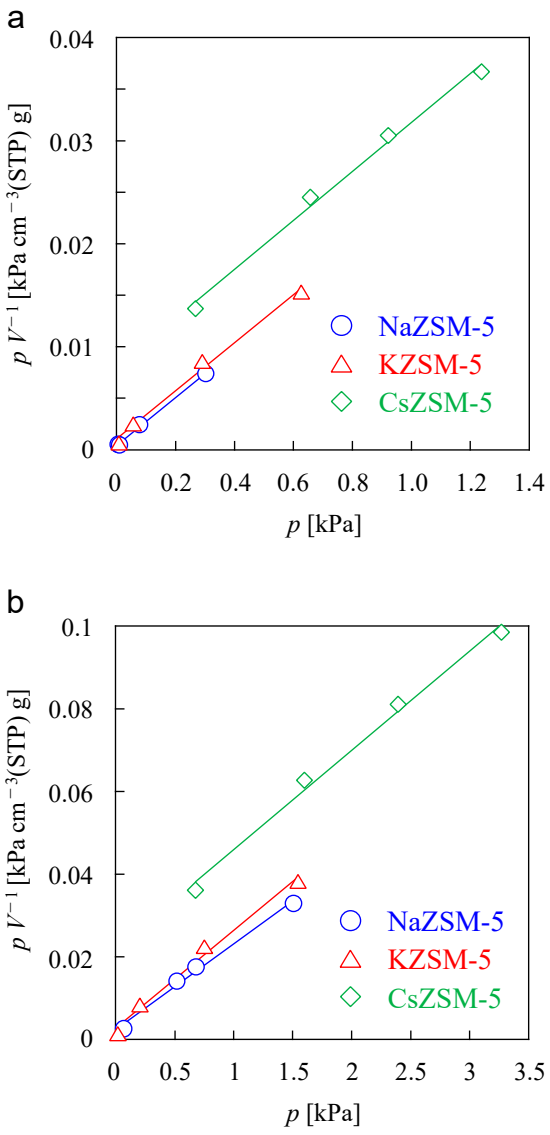


Figure S5. $p\ V^{-1}$ vs p plot of the ZSM-5 powder samples at (a) 323 and (b) 343 K.

6. Langmuir constant

Table S2 lists the calculated values of the Langmuir constant, K.

Table S2. Langmuir constants for the ZSM-5 powder samples.

Temperature [K]	K [kPa^{-1}]		
	NaZSM-5	KZSM-5	CsZSM-5
303	1.5×10^{2}	36	9.0
323	58	23	3.0
343	8.4	8.8	1.1

7. Comparison of separation performance for H_2/SF_6

Figure S6 shows the relationship between H_2 permeance and H_2/SF_6 permselectivity of the synthesized NaZSM-5 membranes and other MFI-type zeolite membranes [30, 37−52].

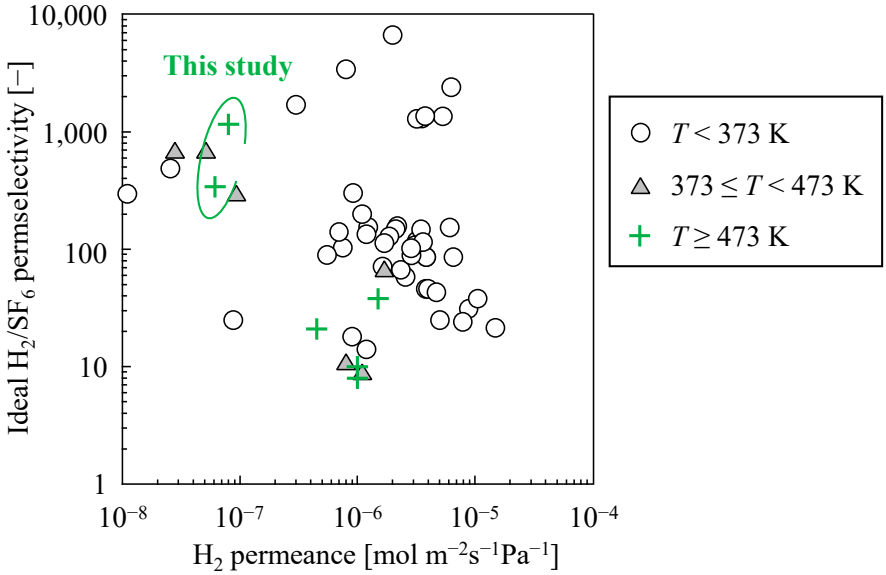


Figure S6. Relationship of H_2 permeance and H_2/SF_6 permeation ratio of MFI-type zeolite membranes.