

## 第5章 問題解答

### 5-1 ドリル問題

1.

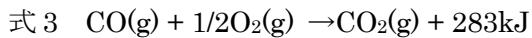
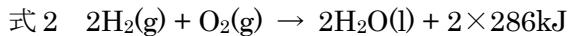
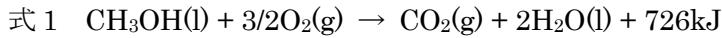
$$N_A = 6.02214 \times 10^{23} \text{ mol}^{-1}, T = 373 \text{ K}, p = 1.01325 \times 10^5 \text{ Pa}, R = N_A k = 8.31447 \text{ J K}^{-1} \text{ mol}^{-1}, M = 1.802 \times 10^{-2} \text{ kg mol}^{-1}, k = 1.38065 \times 10^{-23} \text{ J K}^{-1}, m = 2.992 \times 10^{-26} \text{ kg}$$

$$\bar{c} = \left( \frac{8RT}{\pi M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{ J K}^{-1} \text{ mol}^{-1} \times 373 \text{ K}}{\pi \times 1.802 \times 10^{-2} \text{ kg mol}^{-1}} \right)^{1/2}$$

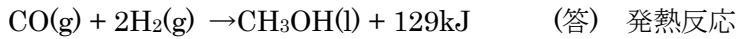
平均速度は、

$$= \left( 4.383 \times 10^5 \frac{\text{kgm}^2 \text{s}^{-2} \text{K}^{-1} \times \text{K}}{\text{kg}} \right)^{1/2} = 6.62 \times 10^2 \text{ ms}^{-1}$$

2.

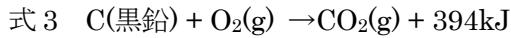
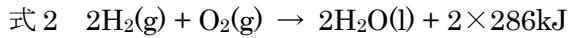


式 2+式 3-式 1 より

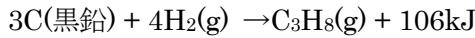


3.

プロパンの燃焼熱は、**2220kJ** の発熱反応である。プロパンの生成熱を求めよ。



(式 2)×2+(式 3)×3-(式 1)より



4.

酸素の衝突断面積  $\sigma = 0.40 \text{ nm}^2$

$$N_A = 6.02214 \times 10^{23} \text{ mol}^{-1} \quad T = 303 \text{ K}, p = 1.01325 \times 10^5 \text{ Pa}$$

$$k = 1.38065 \times 10^{-23} \text{ J K}^{-1}, m = 5.3 \times 10^{-26} \text{ kg},$$

$$R = N_A k = 8.31447 \text{ J K}^{-1} \text{ mol}^{-1}, M = N_A m = 3.2 \times 10^{-2} \text{ kg mol}^{-1}$$

酸素の平均速度：

$$\bar{v} = \left( \frac{8RT}{\pi M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{ J K}^{-1} \text{ mol}^{-1} \times 307 \text{ K}}{\pi \times (3.2 \times 10^{-2} \text{ kg mol}^{-1})} \right)^{1/2}$$

$$= \left( 2.03 \times 10^5 \frac{\text{kgm}^2 \text{s}^{-2} \text{K}^{-1} \text{mol}^{-1} \times \text{K}}{\text{kgmol}^{-1}} \right)^{1/2} = 4.5 \times 10^2 \text{ ms}^{-1}$$

酸素の根平均二乗速度 :

$$\begin{aligned} v &= \left( \frac{3RT}{M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{ J K}^{-1} \text{ mol}^{-1} \times 307 \text{ K}}{3.2 \times 10^{-2} \text{ kg mol}^{-1}} \right)^{1/2} \\ &= \left( 2.39 \times 10^5 \frac{\text{kg m}^2 \text{s}^{-2} \text{K}^{-1} \text{mol}^{-1} \times \text{K}}{\text{kg mol}^{-1}} \right)^{1/2} = 4.9 \times 10^2 \text{ ms}^{-1} \end{aligned}$$

酸素の衝突頻度、

$$\begin{aligned} z &= \frac{\sqrt{2} N_A \bar{\sigma} v p}{RT} \\ &= \frac{\sqrt{2} \times (6.022 \times 10^{23} \text{ mol}^{-1}) \times (0.40 \times 10^{-18} \text{ m}^2) \times (4.5 \times 10^2 \text{ ms}^{-1}) \times (1.01325 \times 10^5 \text{ Pa})}{(8.31447 \text{ Pa m}^3 \text{ K}^{-1} \text{ mol}^{-1}) \times (307 \text{ K})} \\ &= 6.1 \times 10^9 \text{ s}^{-1} \end{aligned}$$

酸素の平均自由行程 :

$$\lambda = \frac{v}{z} = \frac{4.5 \times 10^2 \text{ ms}^{-1}}{6.1 \times 10^9 \text{ s}^{-1}} = 7.4 \times 10^{-8} \text{ m} = 74 \text{ nm}$$

酸素の壁面との衝突数 :

$$\begin{aligned} Z_w &= \frac{\bar{p}v}{4kT} = \frac{(1.01325 \times 10^5 \text{ Pa}) \times (4.5 \times 10^2 \text{ ms}^{-1})}{4 \times (1.38065 \times 10^{-23} \text{ J K}^{-1}) \times (307 \text{ K})} \\ &= 2.7 \times 10^{27} \text{ m}^2 \text{ s}^{-1} = 2.7 \times 10^{23} \text{ cm}^2 \text{ s}^{-1} \end{aligned}$$

5.

アルゴンの衝突断面積  $\sigma = 0.36 \text{ nm}^2$

$N_A = 6.02214 \times 10^{23} \text{ mol}^{-1}$      $T = 288 \text{ K}$ ,  $p = 10^{-5} \text{ Pa}$

$k = 1.38065 \times 10^{-23} \text{ J K}^{-1}$ ,  $m = 6.64 \times 10^{-26} \text{ kg}$ ,

$R = N_A k = 8.31447 \text{ J K}^{-1} \text{ mol}^{-1}$ ,  $M = N_A m = 3.995 \times 10^{-2} \text{ kg mol}^{-1}$

平均速度

$$\begin{aligned} \bar{v} &= \left( \frac{8RT}{\pi M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{ J K}^{-1} \text{ mol}^{-1} \times 288 \text{ K}}{3.1416 \times (3.995 \times 10^{-2} \text{ kg mol}^{-1})} \right)^{1/2} \\ &= \left( 1.53 \times 10^5 \frac{\text{kg m}^2 \text{s}^{-2} \text{K}^{-1} \text{mol}^{-1} \times \text{K}}{\text{kg mol}^{-1}} \right)^{1/2} = 3.9 \times 10^2 \text{ ms}^{-1} \end{aligned}$$

根平均二乗速度

$$\begin{aligned} v &= \left( \frac{3RT}{M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{ J K}^{-1} \text{ mol}^{-1} \times 288 \text{ K}}{3.995 \times 10^{-2} \text{ kg mol}^{-1}} \right)^{1/2} \\ &= \left( 1.80 \times 10^5 \frac{\text{kg m}^2 \text{s}^{-2} \text{K}^{-1} \text{mol}^{-1} \times \text{K}}{\text{kg mol}^{-1}} \right)^{1/2} = 4.2 \times 10^2 \text{ ms}^{-1} \end{aligned}$$

衝突頻度  $z$

$$z = \frac{\sqrt{2} N_A \bar{\sigma} \bar{v} p}{RT}$$

$$= \frac{\sqrt{2} \times (6.022 \times 10^{23} \text{mol}^{-1}) \times (0.36 \times 10^{-18} \text{m}^2) \times (3.9 \times 10^2 \text{ms}^{-1}) \times (10^{-5} \text{Pa})}{(8.31447 \text{Pa m}^3 \text{K}^{-1} \text{mol}^{-1}) \times (288 \text{K})}$$

$$= 0.50 \text{s}^{-1}$$

平均自由行程  $\lambda$

$$\lambda = \frac{v}{z} = \frac{3.9 \times 10^2 \text{ms}^{-1}}{0.50 \text{s}^{-1}} = 7.8 \times 10^2 \text{m}$$

衝突総数  $Z_w$

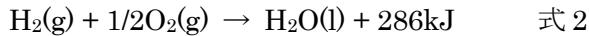
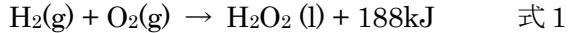
$$Z_w = \frac{p \bar{v}}{4kT} = \frac{(10^{-5} \text{Pa}) \times (3.9 \times 10^2 \text{ms}^{-1})}{4 \times (1.38065 \times 10^{-23} \text{JK}^{-1}) \times (288 \text{K})}$$

$$= 2.5 \times 10^{17} \text{m}^{-2} \text{s}^{-1} = 2.7 \times 10^{13} \text{cm}^{-2} \text{s}^{-1}$$

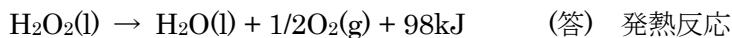
## 第5章 演習問題

1.

過酸化水素の分解反応は、 $\text{H}_2\text{O}_2(\text{l}) \rightarrow \text{H}_2\text{O}(\text{l}) + (1/2)\text{O}_2(\text{g})$



式2-式1より



2.

$$\lambda = \frac{\bar{C}}{Z} = \frac{\bar{C}}{\sqrt{2}\sigma\bar{C}P \frac{1}{kT}} = \frac{kT}{\sqrt{2}\sigma P} = \frac{kT}{\sqrt{2}\sigma \frac{NkT}{V}} = \frac{1}{\sqrt{2}\sigma L[A]}$$

$$\lambda = 2.86 \times 10^{-8} \text{cm} = 2.86 \times 10^{-10} \text{m}, \quad T = 283 \text{K}, \quad k = 1.380662(44) \times 10^{-23} \text{JK}^{-1},$$

$$\sigma = 0.36 \text{nm}^2 = 3.6 \times 10^{-19} \text{m}^2$$

$$\lambda = \frac{kT}{\sqrt{2}\sigma P}$$

$$\therefore P = \frac{kT}{\sqrt{2}\sigma\lambda} = \frac{1.380662 \times 10^{-23} \text{JK}^{-1} \times 283 \text{K}}{\sqrt{2} \times 3.6 \times 10^{-19} \text{m}^2 \times 2.86 \times 10^{-10} \text{m}} = 2.68 \times 10^7 \text{Pa} \quad (\text{答})$$

3.

$$\text{ヘリウムの } \sigma = 0.21 \text{nm}^2 = 2.1 \times 10^{-19} \text{m}^2$$

$$1.0 \text{nTorr} = 1.0 \times 10^{-9} \text{Torr} = 1.0 \times 10^{-9} \times 1.01325 \times 10^5 / 760 \text{Pa} = 1.33 \times 10^{-7} \text{Pa}$$

$$\bar{C} = \left( \frac{8RT}{\pi M} \right)^{1/2} = \left( \frac{8 \times 8.31 \text{JK}^{-1}\text{mol}^{-1} \times 283\text{K}}{\pi \times 4.003 \times 10^{-3} \text{kgmol}^{-1}} \right)^{1/2} = 1.2 \times 10^3 \text{ms}^{-1}$$

$$\begin{aligned}\lambda &= \frac{\bar{C}}{Z} = \frac{\bar{C}}{\sqrt{2}\sigma CP \frac{1}{kT}} = \frac{kT}{\sqrt{2}\sigma P} \\ &= \frac{1.380662 \times 10^{-23} \text{JK}^{-1} \times 283\text{K}}{\sqrt{2} \times 2.1 \times 10^{-19} \text{m}^2 \times 1.33 \times 10^{-7} \text{Pa}} = 9.89 \times 10^4 \text{m} \\ Z_A &= \sqrt{2}\sigma \bar{C}P \frac{1}{kT} = \frac{\sqrt{2} \times 2.1 \times 10^{-19} \text{m}^2 \times 1223 \text{ms}^{-1} \times 1.33 \times 10^{-7} \text{Pa}}{1.380662 \times 10^{-23} \text{JK}^{-1} \times 283\text{K}} = 1.24 \times 10^{-2} \text{m}^2 \text{s}^{-1}\end{aligned}$$

4.

まず平均速度を求める。

$$\begin{aligned}\bar{c} &= \left( \frac{8kT}{\pi n} \right)^{1/2} = \left( \frac{8 \times 1.38065 \times 10^{-23} \text{JK}^{-1} \times 298\text{K}}{3.1416 \times 4.651 \times 10^{-26} \text{kg}} \right)^{1/2} \\ &= \left( 2.253 \times 10^5 \frac{\text{kgm}^2 \text{s}^{-2} \text{K}^{-1} \times \text{K}}{\text{kg}} \right)^{1/2} = 4.75 \times 10^2 \text{ms}^{-1} \\ Zw &= \frac{\bar{pc}}{4kT} = \frac{(1.01325 \times 10^5 \text{Pa}) \times (4.75 \times 10^2 \text{ms}^{-1})}{4 \times (1.38065 \times 10^{-23} \text{JK}^{-1}) \times (298\text{K})} \\ &= 2.92 \times 10^{27} \text{m}^{-2} \text{s}^{-1} = 2.92 \times 10^{23} \text{cm}^{-2} \text{s}^{-1}\end{aligned}$$

2m × 1m × 0.50mの直方体と仮定して体表面積を計算すると、7m<sup>2</sup>となる。

よって、1秒間に2.0 × 10<sup>28</sup>個の窒素ガス分子が衝突している。

5.

理想気体と仮定して計算する。

二酸化炭素の衝突断面積  $\sigma = 0.52 \text{nm}^2$

$N_A = 6.02214 \times 10^{23} \text{ mol}^{-1}$        $T = 473 \text{ K}$ ,  $p = 50 \text{ 気圧} = 5.1 \times 10^6 \text{ Pa}$

$k = 1.38065 \times 10^{-23} \text{ J K}^{-1}$ ,  $m = 7.3 \times 10^{-26} \text{ kg}$ ,

$R = N_A k = 8.31447 \text{ J K}^{-1} \text{ mol}^{-1}$ ,  $M = N_A m = 4.4 \times 10^{-2} \text{ kg mol}^{-1}$

平均速度

$$\begin{aligned}\bar{v} &= \left( \frac{8RT}{\pi M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{JK}^{-1}\text{mol}^{-1} \times 473\text{K}}{3.1416 \times (4.4 \times 10^{-2} \text{kgmol}^{-1})} \right)^{1/2} \\ &= \left( 2.28 \times 10^5 \frac{\text{kgm}^2 \text{s}^{-2} \text{K}^{-1} \text{mol}^{-1} \times \text{K}}{\text{kgmol}^{-1}} \right)^{1/2} = 4.8 \times 10^2 \text{ms}^{-1}\end{aligned}$$

根平均二乗速度

$$\begin{aligned}v &= \left( \frac{3RT}{M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{JK}^{-1}\text{mol}^{-1} \times 473\text{K}}{4.4 \times 10^{-2} \text{kgmol}^{-1}} \right)^{1/2} \\ &= \left( 2.68 \times 10^5 \frac{\text{kgm}^2 \text{s}^{-2} \text{K}^{-1} \text{mol}^{-1} \times \text{K}}{\text{kgmol}^{-1}} \right)^{1/2} = 5.2 \times 10^2 \text{ms}^{-1}\end{aligned}$$

衝突頻度  $z$

$$z = \frac{\sqrt{2}N_A \bar{\sigma} \bar{v} p}{RT}$$

$$= \frac{\sqrt{2} \times (6.022 \times 10^{23} \text{ mol}^{-1}) \times (0.52 \times 10^{-18} \text{ m}^2) \times (4.8 \times 10^2 \text{ ms}^{-1}) \times (5.1 \times 10^6 \text{ Pa})}{(8.31447 \text{ Pa m}^3 \text{ K}^{-1} \text{ mol}^{-1}) \times (473 \text{ K})}$$

$$= 2.8 \times 10^{11} \text{ s}^{-1}$$

平均自由行程  $\lambda$

$$\lambda = \frac{\bar{v}}{z} = \frac{4.8 \times 10^2 \text{ ms}^{-1}}{2.8 \times 10^{11} \text{ s}^{-1}} = 1.7 \times 10^{-9} \text{ m} = 1.7 \text{ nm}$$

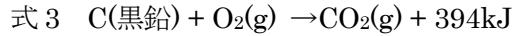
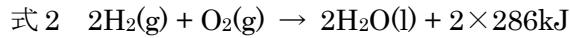
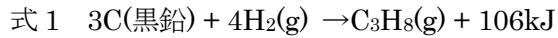
衝突総数  $Z_w$

$$Z_w = \frac{p\bar{v}}{4kT} = \frac{(5.1 \times 10^6 \text{ Pa}) \times (4.89 \times 10^2 \text{ ms}^{-1})}{4 \times (1.38065 \times 10^{-23} \text{ J K}^{-1}) \times (473 \text{ K})}$$

$$= 9.4 \times 10^{28} \text{ m}^{-2} \text{ s}^{-1} = 9.4 \times 10^{24} \text{ cm}^{-2} \text{ s}^{-1}$$

6.

プロパンの生成熱は、106kJである。



(式 2) × 2 + (式 3) × 3 - (式 1) より



7.

100°C、1.00気圧でのベンゼン(気体)において、1モルの体積は、 $V=nRT/P$ より、 $V=0.0306 \text{ m}^3 \text{ mol}^{-1}$ 、  
 $N_A=6.02214 \times 10^{23} \text{ mol}^{-1}$ 、 $T=373 \text{ K}$ 、 $p=1.00\text{atm}=1.01325 \times 10^5 \text{ Pa}$  ( $k=1.38065 \times 10^{-23} \text{ J K}^{-1}$ 、 $R=N_A k=8.31447 \text{ J K}^{-1} \text{ mol}^{-1}$ 、ベンゼンの分子量M=78.1×10<sup>-3</sup> kg mol<sup>-1</sup>、 $m=1.297 \times 10^{-25} \text{ kg}$ ) より

(1) 平均速度

$$\bar{c} = \left( \frac{8RT}{\pi M} \right)^{1/2} = \left( \frac{8 \times 8.31447 \text{ J K}^{-1} \text{ mol}^{-1} \times 373 \text{ K}}{\pi \times (78.1 \times 10^{-3} \text{ kg mol}^{-1})} \right)^{1/2}$$

$$= \left( 1.011 \times 10^5 \frac{\text{kg m}^2 \text{s}^{-2} \text{K}^{-1} \text{mol}^{-1} \times \text{K}}{\text{kg mol}^{-1}} \right)^{1/2}$$

$$= (1.011 \times 10^5 \text{ m}^2 \text{s}^2)^{1/2} = 318 \text{ ms}^{-1}$$

(2) 一分子の衝突回数  $z$

$$z = \sqrt{2} \bar{\sigma} \bar{c} \frac{N}{V} = 7.79 \times 10^9 \text{ 回 s}^{-1}$$

$$= \left[ \frac{\sqrt{2} \times (0.88 \times 10^{-18} \text{ m}^2) \times 318 \text{ ms}^{-1} \times (6.02214 \times 10^{23} \text{ mol}^{-1})}{30.6 \times 10^{-3} \text{ m}^3 \text{ mol}^{-1}} \right]$$

$$= \sqrt{2} \bar{\sigma} \bar{c} p \frac{1}{kT} = 7.79 \times 10^9 \text{ 回 s}^{-1}$$

(3) 平均自由行程  $\lambda$

$$\begin{aligned}\lambda &= \frac{\bar{c}}{z} = \frac{318\text{ms}^{-1}}{7.79 \times 10^9 \text{s}^{-1}} = 4.08 \times 10^{-8} \text{m} \\ &= \frac{RT}{\sqrt{2}N_A\sigma p} = \frac{(8.31447\text{JK}^{-1}\text{mol}^{-1}) \times 373\text{K}}{\sqrt{2} \times (6.02214 \times 10^{23} \text{mol}^{-1}) \times (0.88 \times 10^{-18} \text{m}^2) \times (1.01325 \times 10^5 \text{Pa})} \\ &= \frac{kT}{\sqrt{2}\sigma p} = \frac{(1.38065 \times 10^{-23} \text{JK}^{-1}) \times 373\text{K}}{\sqrt{2} \times (0.88 \times 10^{-18} \text{m}^2) \times (1.01325 \times 10^5 \text{Pa})} = 4.08 \times 10^{-8} \text{m}\end{aligned}$$

(4) 気体中の全分子の間の全衝突頻度  $Z_{AA}$

$$\begin{aligned}Z_{AA} &= \frac{1}{2} z \frac{N}{V} = \frac{1}{2} \times (7.79 \times 10^9 \text{s}^{-1}) \times \frac{6.02214 \times 10^{23} \text{mol}^{-1}}{0.0306 \text{m}^3 \text{mol}^{-1}} = 7.67 \times 10^{34} \text{m}^{-3} \text{s}^{-1} \\ Z_{AA} &= \frac{1}{2} \left( \sqrt{2} \bar{\sigma c} \frac{N}{V} \right) \frac{N}{V} = \frac{\bar{\sigma c}}{\sqrt{2}} \left( \frac{N}{V} \right)^2 \\ &= \frac{1}{2} \times \left( \frac{\sqrt{2} \times (0.88 \times 10^{-18} \text{m}^2) \times 318 \text{ms}^{-1} \times (6.02214 \times 10^{23} \text{mol}^{-1})}{30.6 \times 10^{-3} \text{m}^3 \text{mol}^{-1}} \right) \times \frac{6.02214 \times 10^{23} \text{mol}^{-1}}{0.0306 \text{m}^3 \text{mol}^{-1}} \\ &= 7.67 \times 10^{34} \text{m}^{-3} \text{s}^{-1}\end{aligned}$$

(5) 容器への衝突回数  $Z_w$

$$\begin{aligned}Z_w &= \left( \frac{kT}{2\pi n} \right)^{1/2} \frac{N}{V} = \left( \frac{(1.38065 \times 10^{-23} \text{JK}^{-1}) \times 373\text{K}}{2 \times \pi \times (1.297 \times 10^{-25} \text{kg})} \right)^{1/2} \times \frac{6.02214 \times 10^{23} \text{mol}^{-1}}{0.0306 \text{m}^3 \text{mol}^{-1}} \\ &= 79.49 \times 1.968 \times 10^{25} \text{m}^{-3} = 1.56 \times 10^{27} \text{m}^{-2} \text{s}^{-1}\end{aligned}$$

$$Z_w = \frac{\bar{c}N}{4V} = \frac{318\text{ms}^{-1}}{4} \times \frac{6.02214 \times 10^{23} \text{mol}^{-1}}{0.0306 \text{m}^3 \text{mol}^{-1}} = 1.56 \times 10^{27} \text{m}^{-2} \text{s}^{-1}$$

$$Z_w = \frac{\bar{p}c}{4kT} = \frac{(1.01325 \times 10^5 \text{Pa}) \times 318 \text{ms}^{-1}}{4 \times (1.38065 \times 10^{-23} \text{JK}^{-1}) \times 373\text{K}} = 1.56 \times 10^{27} \text{m}^{-2} \text{s}^{-1}$$

$$\begin{aligned}Z_w &= \frac{p}{(2\pi nkT)^{1/2}} = \frac{1.01325 \times 10^5 \text{Pa}}{(2 \times \pi \times (1.297 \times 10^{-25} \text{kg}) \times (1.38065 \times 10^{-23} \text{JK}^{-1}) \times 373\text{K})^{1/2}} \\ &= \frac{1.01325 \times 10^5 \text{kgm}^{-1} \text{s}^{-2}}{6.478 \times 10^{-23} \text{kgms}^{-1}} = 1.56 \times 10^{27} \text{m}^{-2} \text{s}^{-1}\end{aligned}$$