Technical Notes

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Temperature Changes in Nonisoenthalpic Throttling Processes of Some Real Gases

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Nomenclature

A	=	cross-sectional area of a test tube, m^2
a, b	=	parameters in the Redlich–Kwong equation
C_p	=	isobaric specific heat, J/kg K
h	=	specific enthalpy, J/kg
K	=	thermal conductance, W/K
k_V	=	thermal conductivity of a throttle valve, W/mK
$\dot{m}$	=	mass flow rate, kg/s
P	=	pressure, Pa
q_{12}	=	amount of heat exchanged between a flowing gas and an environment, J/kg
R	=	gas constant, J/kg K
r_V	=	effective radius of a throttle valve, m
T	=	temperature, K
v	=	specific volume, m^3/kg
$\dot{V}$	=	volumetric flow rate, m^3/s
w	=	velocity, m/s
y_V	=	distance between the wall of a vacuum chamber and the wall of a test tube, m
μ_{JT}	=	Joule–Thomson coefficient, K/Pa
π	=	ratio of the circumference of a circle to its diameter
ρ	=	density of fluid, kg/m^3

Subscripts

W	=	wall of a vacuum chamber
1	=	upstream
2	=	downstream

Introduction

In isoenthalpic throttling processes of real gases [1], cooling or heating occur owing to intermolecular forces acting among molecules. Particularly, some kinds of gas resulting in cooling through a throttle near room temperature are of practical importance in relating to refrigeration of materials. However, a pure isoenthalpic process is scarcely achieved in actual equipment such as refrigerators and gas liquefiers, owing to heat exchanges between a flowing gas and an environment and changes in fluid velocity through a throttle.

The purpose of the present Note is to experimentally and theoretically study temperature changes in nonisoenthalpic throttling processes of CO_2, N_2, and H_2, of which the Joule–Thomson coefficients are positive, nearly zero, and negative around atmospheric conditions, respectively.

Experiment

A schematic diagram of the experimental apparatus is shown in Fig. 1. The test tube is a circular SUS304 stainless steel pipe of 10-mm o.d. and 2 mm in thickness and was placed within a SUS304 stainless steel vacuum chamber of 72-mm i.d. and 300 mm in length, which was evacuated continuously to below 1 kPa using a rotary vacuum pump. A SUS316 stainless steel needle valve was used as a throttle. Pressure taps for measuring fluid temperature and mixing chambers for measuring fluid temperature were installed before and behind the throttle. Two sets of type-K sheathed thermocouple of 1-mm sheath diameter were inserted into each mixing chamber. The uncertainty in the measured value of a temperature difference of fluids within two mixing chambers was estimated to be ± 0.26 K. The gas pressure upstream of the throttle value was measured using a digital pressure sensor and was varied from 3 to 7 bar (gauge), and the outlet gas pressure was kept at atmospheric pressure. The minimum display reading on the pressure sensor is 1 kPa, and the relative uncertainty in the measured value of a pressure difference across the throttle was estimated to be $\pm 0.25\%$. A test gas was supplied from a high-pressure bomb and was kept at room temperature using a constant temperature water bath and then was fed to a test section. The gas flow rate $\dot{V}$, which was measured using a rotameter, was varied from 0.4 to 10 Nl/min. The minimum reading on the rotameter was 0.025 Nl/min. The mass flow rate $\dot{m}$ was estimated from $\rho\dot{V}$. The relative uncertainty in estimating $\dot{m}$ was $\pm 6.25\%$. Three kinds of gas [i.e., CO_2(99.5%), N_2(99.99%), and H_2(99.99%)] were used as test gases. It took about 0.5 h to attain the steady state at each flow rate.

Analysis

The conservation of energy for a one-dimensional flow [2] may be written as follows:

$$q_{12} = h_2 - h_1 + \tfrac{1}{2}\left(w_2^2 - w_1^2\right) \tag{1}$$

where $\frac{1}{2}(w_2^2 - w_1^2)$ represents a change in kinetic energy, and h_1 and h_2 are enthalpies upstream and downstream of the throttle, respectively. In the present experimental system, heat exchanges between a flowing medium and an environment is governed by heat conduction through the needle valve, because radiation heat transfer between the inner surface of the vacuum chamber and the outer surface of the test tube can be disregarded. Thus, q_{12} may be written as

$$q_{12} = (K/\dot{m})[T_W - (T_1 + T_2)/2] \text{ [J/kg]} \tag{2}$$

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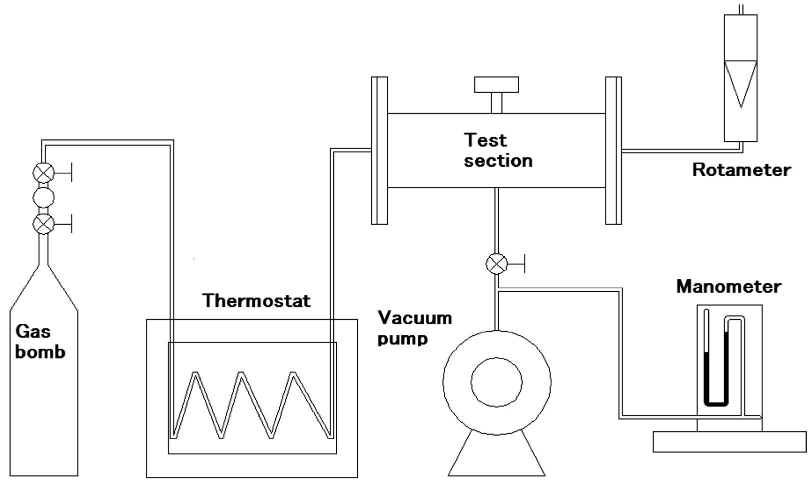

Fig. 1 Schematic diagram of the experimental apparatus.

$$K = \pi r_v^2 k_v / y_v \ [\mathrm{W/K}] \tag{3}$$

where T_W denotes a mean wall temperature of the vacuum chamber, k_V is the thermal conductivity of the SUS316 needle valve ($\approx$16.7 W/mK), r_V is an effective radius of the needle valve ($\approx$0.007 m), and y_V is $\approx$0.033 m. With these values, K was estimated to be about 0.08 W/K.

Moreover, the conservation of mass yields

$$\dot{m} = \rho_1 w_1 A = \rho_2 w_2 A \tag{4}$$

where ρ_1 and ρ_2, respectively, represent fluid densities before and behind the throttle value. We assume that ρ_1 and ρ_2 can be evaluated using the equation of state of an ideal gas: $\rho = P/RT$.

Thus, we can obtain

$$h_2 - h_1 = \frac{1}{2}\frac{\dot{m}^2 R^2}{A^2}\left[\frac{T_1^2}{P_1^2} - \frac{T_2^2}{P_2^2}\right] + \frac{K}{\dot{m}}\left[T_W - \frac{(T_1 + T_2)}{2}\right] \tag{5}$$

Next, we must explicitly represent h in terms of T and P, and thus we assume that h is a function of T and P:

$$\mathrm{d}\,h = \left(\frac{\partial h}{\partial T}\right)_P \mathrm{d}T + \left(\frac{\partial h}{\partial P}\right)_T \mathrm{d}P \tag{6}$$

Because the Joule–Thomson coefficient and the isobaric specific heat are, respectively, defined as

$$\mu_{\mathrm{JT}} = \left(\frac{\partial T}{\partial P}\right)_h, \qquad C_P = \left(\frac{\partial h}{\partial T}\right)_P$$

then we can obtain the following relation using a chain rule with respect to T, P, and h:

$$\left(\frac{\partial h}{\partial P}\right)_T = -C_P \mu_{\mathrm{JT}}$$

Consequently, Eq. (6) is rewritten as

$$\mathrm{d}\,h = C_P(\mathrm{d}T - \mu_{\mathrm{JT}}\mathrm{d}P) \tag{7}$$

If C_p and μ_{JT} are constant in the experimental range, integrating Eq. (7) along the flow direction yields

$$h_2 - h_1 = C_P(T_2 - T_1) - \mu_{\mathrm{JT}} C_P (P_2 - P_1) \tag{8}$$

Combining Eqs. (5) and (8) results in an analytical expression for T_2:

$$\begin{gathered} T_2 = \frac{A^2 P_2^2 (2\dot{m}C_P + K)}{2\dot{m}^3 R^2}\left[-1 + \sqrt{1 - \frac{8\dot{m}^4 C_P R^2 \Gamma}{A^2 P_2^2 (2\dot{m}C_P + K)^2}}\right] \\ \Gamma = \mu_{\mathrm{JT}}(P_1 - P_2) - \frac{\dot{m}^2 R^2 T_1^2}{2 C_P A^2 P_1^2} - \frac{K}{\dot{m}C_P}\left(T_W - \frac{T_1}{2}\right) - T_1 \end{gathered} \tag{9}$$

Because the Joule–Thomson coefficient μ_{JT} is represented as

$$\mu_{\mathrm{JT}} = \left[T\left(\frac{\partial v}{\partial T}\right)_P - v\right] \Big/ C_P \tag{10}$$

then μ_{JT} can be calculated from an equation of state of a real gas. We adopted the Redlich–Kwong equation (11) [3,4], because this equation has gained a reputation to be fairly reliable in predicting μ_{JT}:

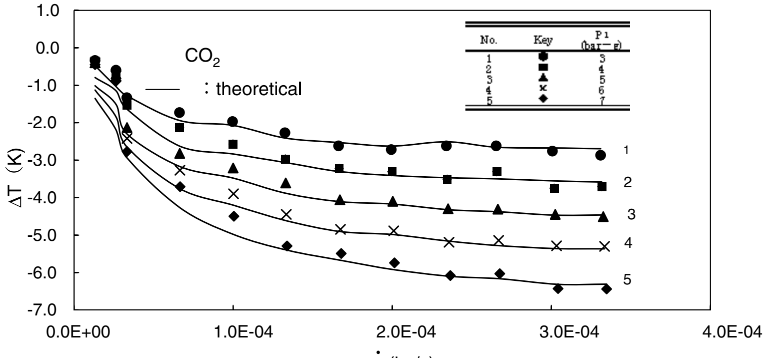

Fig. 2 Relations between ΔT and $\dot{m}$ for CO_2 gas flows.

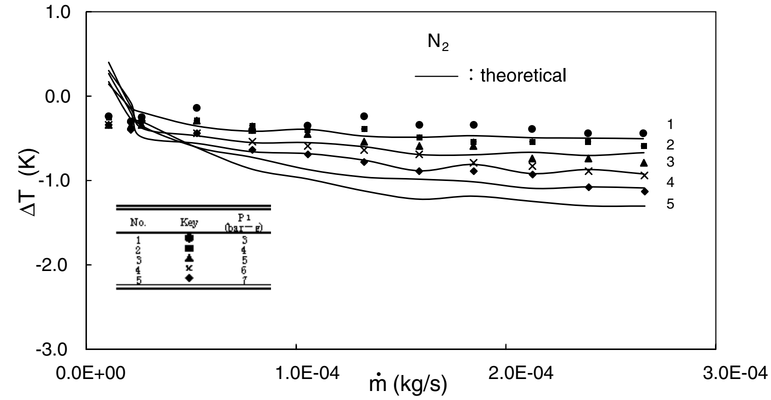

Fig. 3 Relations between ΔT and $\dot{m}$ for N_2 gas flows.

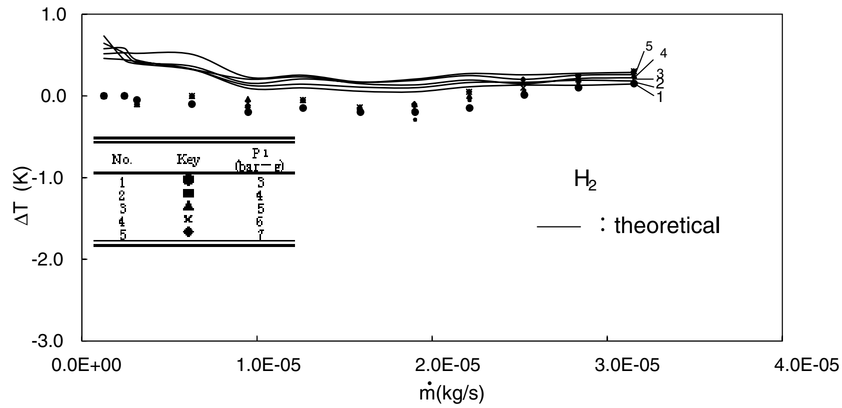

Fig. 4 Relations between ΔT and $\dot{m}$ for H_2 gas flows.

$$P = \frac{RT}{v-b} - \frac{a}{v(v+b)\sqrt{T}} \tag{11}$$

Results and Discussion

Obtained relations between a temperature difference across the throttle valve [$\Delta T = T_2 - T_1$ (K)] and a mass flow rate $\dot{m}$ (kg/s) are shown in Figs. 2–4, in which the solid lines indicate theoretical predictions based on Eqs. (9). It is seen from these figures that ΔT tends to become constant with an increase in $\dot{m}$, which is caused by the fact that as $\dot{m}$ increases, an amount of heat exchanged between a flowing gas and an environment per unit mass of a flowing gas (i.e., q_{12}) decreases to a zero and ΔT is asymptotic to a value given by $\mu_{\mathrm{JT}}(P_2 - P_1)$. Moreover, it is found that, in accord with a value of the Joule–Thomson coefficient, an asymptotic temperature difference becomes negative for $\mu_{\mathrm{JT}} > 0$ and positive for $\mu_{\mathrm{JT}} < 0$. An estimate of a change in kinetic energy shows that this contribution can be fully disregarded. Agreement between theoretical predictions and experimental results is acceptable within uncertainties involved in the experimental measurements.

Conclusions

Temperature changes in nonisoenthalpic throttling processes of some real gases can be reasonably predicted by considering heat exchanges between a flowing gas and an environment: with an increase in mass flow rate, the temperature difference before and behind a throttle ΔT is asymptotic to a constant value estimated by $\mu_{\mathrm{JT}}\Delta P$.

References

[1] Joule, J. P., and Thomson, W., "On the Thermal Effects of Fluids in Motion, Part 2," *Philosophical Transactions of the Royal Society of London*, Vol. 144, 1854, pp. 321–364.

[2] Ito, T., and Yamashita, H., *Engineering Thermodynamics*, Vol. 1, Corona, Tokyo, 1994, p. 31.

[3] Redlich, O., and Kwong, J. N. S., "On the Thermodynamics of Solutions, 5," *Chemical Reviews (Washington, DC)*, Vol. 44, 1949, pp. 233–244.

[4] Bejain, A., *Advanced Engineering Thermodynamics*, Wiley, New York, 1987, p. 283.