Calibration of a Slotted Disk Velocity Selector Using Supersonic Molecular Beams *

P. CANTINI, M. G. DONDI, and F. TORELLO **

Istituto di Scienze Fisiche dell'Università, 16132 Genova, Italy

(Z. Naturforsch. **26 a**, 1634—1638 [1971]; received 29 May 1971)

A new calibration method for slotted disk velocity selectors is presented and is compared with other calibration procedures.

It is based on the measurement of the velocity distribution of a supersonic molecular beam produced by a room temperature source.

The error due to the assumed theoretical distribution and to experimental procedure is discussed. It is shown that the velocity scale is known to within 0.8%.

Introduction

Slotted disks velocity selectors (SDVS) are widely used to produce molecular beams with a well defined velocity and to study the velocity distribution of beams produced by effusive or hypersonic sources.

The relevant characteristics of SDVS (velocity resolution, transparence, sidebands elimination) have been widely discussed[1–4]. They are evaluated from the geometry of the rotor assembly but may be influenced by the experimental conditions (angular divergence of the beam; misalignment with the rotor axis). In particular the velocity of the selected particles may not correspond to the nominal one. On the other hand, improvements in the experimental techniques of beam production and detection, for alkali and, more recently, for non-alkali systems, allow the resolution of many different "lines" in the "collisional spectra" of these substances. However, the information content is strictly correlated[5,6] to the uncertainty in the velocity scale.

In this note a new method of velocity selector calibration, using supersonic molecular beams, is reported. The assumed velocity distribution is discussed taking into account some recent experimental[7] and theoretical results[8,9]. The advantages and disadvantages of this method are discussed and compared with other calibration procedures[10–12].

Calibration Methods

A velocity selector rotating at a frequency ν transmits molecules in a well defined velocity range. The maximum of the transmission is given at the nominal velocity v_0 which, in the ideal conditions (beam with no angular divergence and parallel to the selector axis) is given by

$$v_0 = (2\pi L/\Phi) \cdot \nu \qquad (1)$$

where Φ is the angular shift and L is the distance between the first and the last disk. The quantity $2\pi L/\Phi$ is the nominal calibration factor (f_0) of the selector.

The transmitted velocity distribution is

$$T(v_0) = \int_0^\infty I(v)\, B(v, v_0)\, \mathrm{d}v \qquad (2)$$

where $B(v, v_0)$[1] is the transmission function and $I(v)$ is the velocity distribution of the beam. If the beam is not parallel to the selector axis the angle Φ may be replaced by an effective angle $\Phi + \Delta$, and the nominal calibration factor f_0 by the effective calibration factor

$$f = 2\pi L/(\Phi + \Delta) \qquad (3)$$

* Work supported by the Italian National Research Council through the Gruppo Nazionale di Struttura della Materia.

** Present address: Max Planck Institut für Strömungsforschung, Göttingen, Germany.

[1] H. U. HOSTETTLER and R. B. BERNSTEIN, Rev. Sci. Instrum. **31**, 872 [1960].

[2] S. M. TRUJILLO, P. K. ROL, and E. W. ROTHE, Rev. Sci. Instrum. **33**, 841 [1962].

[3] J. L. KINSEY, Rev. Sci. Instrum. **37**, 61 [1966].

[4] R. K. HELBING, Dissertation Bonn 1966.

[5] U. BUCK and H. PAULY, J. Chem. Phys., **54**, 1929 [1971].

[6] P. CANTINI, M. G. DONDI, G. SCOLES, and F. TORELLO, J. Chem. Phys., to be published.

[7] F. TORELLO, AIAA J. to be published and references cited there.

[8] R. H. EDWARDS and H. K. CHENG, Proc. V Rar. Gas Dyn (ed. Brundin), Acad. Press New York 1967, p. 819.

[9] N. C. FREEMAN and D. R. THOMAS, Proc. VI Rar. Gas Dyn. (ed. Trilling and Wachmann) Acad. Press, New York 1969, p. 163.

while the transmission function is weakly dependent on the angle Δ[1]. It is generally experimentally difficult to make Δ negligible in respect to Φ by optical alignment due to the constraints of the experimental set up. For this reason different in situ calibration techniques have been used which can be schematically grouped as follows:

a) methods which use mainly the geometric properties of the selector,

b) methods which use the knowledge of the velocity distribution of a reference beam.

In the case a) selectors which allow the choice of two different ranges of velocity for the transmitted particles, corresponding to clockwise or counterclockwise rotation, are used[13]. By comparing the different measured frequencies corresponding to the same velocity (often the maximum of the transmitted distribution) it is possible to determine the angle Δ. In this case attention must be paid to the fact that the maxima of the transmitted distribution may not correspond to the same velocity, especially for narrow distribution and non symmetric transmission function. This method was recently improved using symmetric selectors[10,11] i.e. with the same characteristic (including the transmission function) when they rotate clockwise and counterclockwise. In this case the calibration is completely independent of the beam properties. Symmetric selectors are not always available and convenient. Some authors use inclined tooth selectors[3,14] in order to increase the transparency; therefore, no arrangement of the disks can give a symmetric selector in this case.

In case b) a theoretical velocity distribution is compared with the experimental intensity as a function of the rotor frequency. This method has been generally used with maxwellian beams effused from a source at a known temperature. Due to the relatively small intensity of such a beam, sensitive detectors are required. The background pressure must be low enough to avoid changes in the shape of the velocity distribution due to velocity dependent[15,16] scattering of the beam molecules by residual gases. It is very hard to fulfil these two conditions for non alkali beams. We describe here a calibration method which avoids these difficulties by using a supersonic molecular beam.

Velocity Distribution of a Supersonic Molecular Beam

A supersonic molecular beam is produced by sampling a free expanding jet with a collimator of proper shape called a skimmer. Because of the different flow conditions along a single flow line, the problem of free expanding jets is not jet completely understood even in the relatively simple case of an ideal monatomic gas. HAMEL and WILLIS[17] proposed a maxwellian distribution function with respect to the bulk velocity separated into two factors for the degrees of freedom parallel and perpendicular to a flow line (ellipsoidal model). The mean random velocities parallel and perpendicular to the flow are generally different ($C_\parallel$, $C_\perp$) and define the "temperatures" $T_\parallel$ and $T_\perp$ via the usual equation:

$$C_{\parallel/\perp} = \sqrt{2KT_{\parallel/\perp}/m}$$

where K is the Boltzmann constant and m is the molecular mass. Experimental results[7] and theoretical calculation[8] have shown that the ellipsoidal model is a good approximation for the real distribution. The agreement is particularly good for the parallel distribution, so that the usual velocity distribution for a supersonic beam[18] is assumed to be

$$f(v)\,\mathrm{d}v \propto v^3 \exp[-(m/2KT_\parallel)\cdot(v-u)^2]\,\mathrm{d}v \quad (4)$$

where u is the bulk velocity and $T_\parallel$ the parallel temperature at the skimmer. Introducing the dimensionless velocity x

$$x = v(2KT_0/m)^{-1/2}$$

where T_0 is the source temperature, and the parallel speed ratio $S_\parallel$ defined by:

$$S_\parallel = u(2KT_\parallel/m)^{-1/2}$$

[10] U. BUCK, Dissertation, Bonn 1969.
[11] D. BECK and H. FÖRSTER, Z. Physik **240**, 136 [1970].
[12] K. T. GILLEN, C. RILEY, and R. B. BERNSTEIN, J. Chem. Phys. **50**, 4019 [1969].
[13] A. E. GROSSER, Rev. Sci. Instrum. **38**, 257 [1967].
[14] J. E. SCOTT, H. S. MORTON, J. A. PHIPPS, and J. F. MOONAN, Proc. IV Rar. Gas Dyn. (de Leeuw ed.). Academic Press, New York 1966, p. 331.
[15] I. ESTERMANN, O. C. SIMPSON, and O. STERN, Phys. Rev. **71**, 238 [1947].
[16] I. AMDUR, G. STARKSCHALL, A. M. FALICK, and R. R. BERTRAND, Entropie **30**, 30 [1969].
[17] B. B. HAMEL and D. R. WILLIS, Phys. Fluids **9**, 829 [1966].
[18] J. B. ANDERSON and J. B. FENN, Phys. of Fluids **8**, 780 [1965].

Eq. (4) becomes:

$$g(x)\,dx \propto x^3 \exp\left[-\left(\sqrt{\frac{T_0}{T_\parallel}}\,x - S_\parallel\right)^2\right] dx. \quad (5)$$

The energy conservation law for a monatomic gas combined with the hypothesis of adiabatic expansion and an ellipsoidal velocity distribution gives[19]

$$\tfrac{5}{2}KT_0 = \tfrac{1}{2}mu^2 + \tfrac{3}{2}KT_\parallel + KT_\perp. \quad (6)$$

For isotropic temperature at the skimmer ($T_\perp = T_\parallel$)

$$T_0/T_\parallel = 1 + \tfrac{2}{5}S_\parallel{}^2 \quad (7)$$

while in the limiting situation of $T_\perp/T_\parallel \ll 1$

$$T_0/T_\parallel = \tfrac{3}{5} + \tfrac{2}{5}S_\parallel{}^2. \quad (8)$$

Taking into account Eqs. (7) and (8), the dimensionless velocity distribution is

$$g(x)\,dx \propto x^3 \exp[-(x\sqrt{a + \tfrac{2}{5}S_\parallel{}^2} - S_\parallel)^2]\,dx \quad (9)$$

where a lies between 3/5 and 1. Eq. (9) like Eq. (4), contains two parameters, but at high $S_\parallel$ values ($S_\parallel \gtrsim 10$) the dimensionless most probable velocity x_M is almost independent of $S_\parallel$ and is very weakly dependent on a.

In Fig. 1 the x_M values as a function of $S_\parallel$ for the two limiting values of a are reported. In the same figure the x_M values for a equal to zero, which correspond to the usual approximation obtained by replacing the bulk velocity with its limiting ($S_\parallel \to \infty$) value $u_\infty = \sqrt{\frac{5}{2}\,2KT_0/m}$, are also shown.

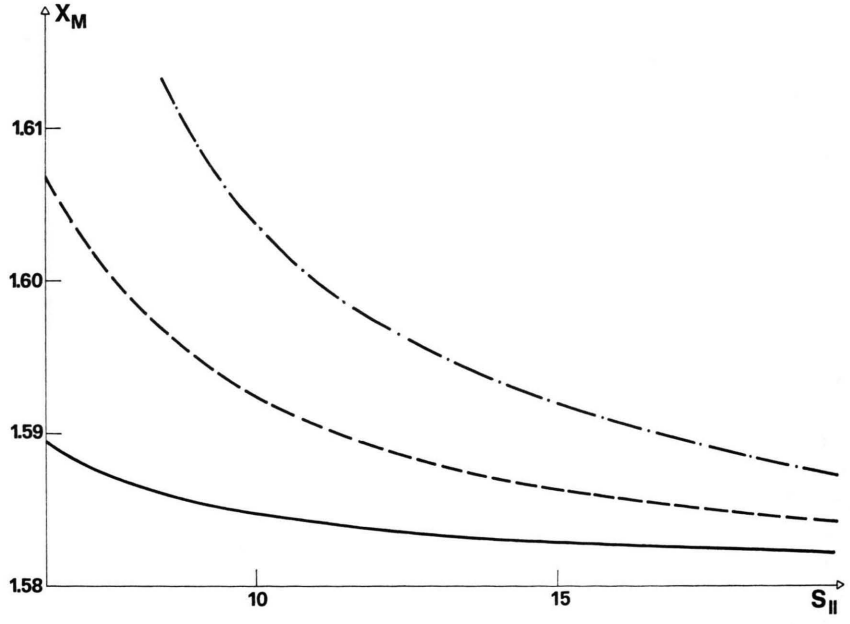

Fig. 1. x_M as a function of $S_\parallel$: — $a = 1$; — — — $a = \frac{3}{5}$; —·—·— $a = 0$.

Table 1. Specifications of the velocity selector (manufactured by Gersing & Hess, Bonn, Germany).

Number of disks	6
Disk diameter	158.6 mm
Disk thickness	1.5 mm
Number of slits per disk	280
Length of slits (in radial direction)	8 mm
Slit width	0.8 mm
Wall thickness between slits:	
at base of slits	0.8 mm
at top of slits	0.89 mm
L	100.35 mm
∅	0.1683 rad.
Resolution (F. W. H. M.)	5.03%

The nozzles used were 0,027 and 0,063 mm in diameter and the skimmer diameter was 0.41 mm. The nozzle-skimmer distance was 3.5 mm. Typical background pressures were $5 \cdot 10^{-5}$ torr in the expansion chamber and $1 \cdot 10^{-6}$ torr in the detection chamber.

We carefully measured the nozzle temperature to avoid systematic errors. The nozzle, made of copper, is in good thermal contact with a thermostat, filled with water several hours before the

Experimental

Velocity distribution of supersonic molecular beams were measured in an apparatus built for the study of the energy dependence of He^4-He^4 integral collision cross sections[20]. Relevent dimensions of the selector are given in Table 1.

[19] E. L. KNUTH and S. S. FISHER, J. Chem. Phys. **48**, 1674 [1968].

measurements at a temperature T_0 (see Fig. 1, Ref. 6); T_0 is measured with a mercury thermometer to within 0.1 °C. A platinum resistance thermometer is used to check that the source temperature remains constant when gas flows through the nozzle.

All the distributions were measured at room temperature. Several monatomic gases (Ne, Ar, Kr) of commercial purity were used at various stagnation pressures.

The theoretical intensity at the detector $I(x_0)$ is computed by numerical integration of the equation.

$$I(x_0) \propto \int_0^\infty g(x)\, E(x)\, B'(x, x_0)\, \mathrm{d}x \qquad (10)$$

where $B'(x, x_0)$ is the transmission function of the selector, $E(x)$ is the efficiency of the detector (in our case it is assumed to be proportional to x^2). By comparison of the experimental intensities as a function of the selector rotational speed with $I(x_0)$ (with $a = 1$ in $g(x)$) on a log-log plot, we determined, for the best $S_\parallel$ value, the factor c between the dimensionless velocity and the frequency scale. The calibration factor of the selector f is thus obtained multiplying c by $(2KT_0/m)^{1/2}$ where T_0 is the measured nozzle temperature. In Table 2 the f values obtained in different experimental conditions are reported. No systematic variation of f for the different gases used and for the various speed ratios seems present. The standard deviation of f from its mean value is 0.6%; an additional error of 0.2% is due to the uncertainty in the parameter a. The measured value of the calibration factor is 3.1% less than the nominal one; the misalignment angle between beam direction and selector axis is thus $3{,}72 \times 10^{-3}$ rad.

Table 2. $S_\parallel$ and f values (in m sec^{-1} Hz^{-1}) obtained under different experimental conditions [P_0 is the stagnation pressure in the nozzle (in Torr.), T_0 is the nozzle temperature (°K), N_d is the nozzle diameter (in mm.)].

Gas	P_0	T_0	N_d	$S_\parallel$	f
Argon	209.4	298.2	.063	11.0	3.626
	219.5	298.8	.063	11.2	3.636
	221.6	298.1	.063	11.4	3.618
	507.4	298.4	.027	11.8	3.637
	708.7	298.6	.027	13.0	3.641
Krypton	153.7	297.9	.063	10.2	3.682
	152.6	298.2	.063	10.2	3.604
	516.5	297.2	.027	12.4	3.598
	516.0	297.3	.027	12.4	3.594
	715.2	297.0	.027	13.4	3.614
	717.0	297.0	.027	13.6	3.615
Neon	713.0	295.5	.027	10.0	3.656
	712.0	295.5	.027	10.0	3.641

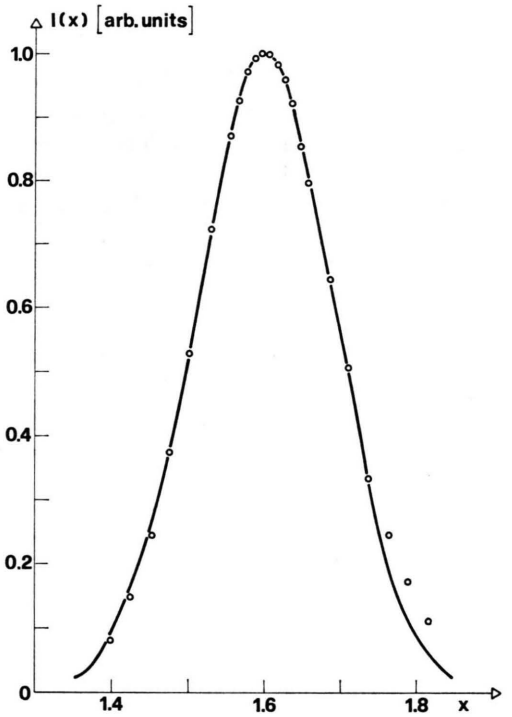

Fig. 2. A typical measured distribution as a function of the reduced velocity (Gas: Argon; nozzle diameter 0.027 mm; stagnation pressure 708.7 Torr; nozzle temperature 298.6 °K). The solid curve is the calculated energy flux distribution [Eq. (10)] with $S_\parallel$ equal to 13.0.

In Fig. 2 a measured distribution is reported; the full line is the normalized theoretical curve [Eq. (10)] with the $S_\parallel$ value which gives the best fit. The error on $S_\parallel$ is in any case less than 2%. It is apparent that the assumed velocity distribution agrees very well with the measured intensities; there is only a small deviation at high velocities where the experimental curve has a higher tail, in agreement with measurements of several authors[21,22]. Probably the assumed velocity distribution is inadequate at

[20] M. G. Dondi, G. Scoles, F. Torello, and H. Pauly, J. Chem. Phys. **51**, 392 [1969].

[21] J. E. Scott and J. A. Phipps, Proc. V Rar. Gas Dyn. (ed. Brundin) Academic Press, New York 1967, p. 1337.

[22] N. Abuaf, J. B. Anderson, R. P. Andres, J. B. Fenn, and D. R. Miller, ibidem, p. 1317.

high velocities. At lower source pressures the theoretical curve gives a poorer fit to the experimental results. There is an excess of fast molecules and deficiency of slow ones, in agreement with previous measurements of velocity distributions in supersonic beams with low $S_{\|}$ [21–23], and in effusive beams [14, 24–27].

Conclusions

The velocity selector calibration was made in situ with the same experimental apparatus used in the He^4-He^4 integral cross section experiments. The error in the velocity scale is comparable with those obtained in accurate calibrations using symmetric selector techniques [10, 11] or measuring maxwellian distribution of alkali beams [12]. The two main advantages of the calibration reported here are the use of a source whose temperature can easily be determined with high accuracy and its applicability to any kind of selector. Supersonic beams produce large signals at the detector and, due to their narrow distribution, the velocity dependent background scattering changes the shape of the velocity distribution by a smaller amount. Classical beams have the advantage that the distribution function is predicted by exact kinetic theory, but in order to have a Maxwell-Boltzmann equilibrium distribution, measurements must be taken at quite high source Knudsen number ($Kn \gtrsim 10$), thus obtaining beams of relatively small intensity.

Acknowledgements

Discussions with professors D. R. Miller, H. Pauly, G. Scoles and J. E. Scott are gratefully acknowledged.

[23] S. S. Fisher, Tech. Rept. UCLA n.° 67—5, Los Angeles 1967.
[24] R. C. Miller and P. Kusch, Phys. Rev. **99**, 1314 (1955).
[25] P. M. Marcus and J. H. McFee, Recent Research in Molecular Beam (Esterman ed.) Academic Press, New York 1959, p. 43.
[26] Y. S. Lou and R. E. Stikney, Phys. Fluids **13**, 528 [1970].
[27] P. B. Scott, P. H. Bauer, H. Y. Wachman, and L. Trilling, Proc. V Rar. Gas Dyn. (Brundin ed.), Academic Press, New York 1967, p. 1353.