Heavy gas mixtures for wind tunnel use

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INTRODUCTION

The advantages of using heavy gases in wind tunnels — reduced power consumption and scale size — have been appreciated for some time[1]. To be sure of correct scaling of the results from such a tunnel, the working fluid should have a specific-heat-ratio γ equal to that of air ($\gamma = 1\cdot4$); such a fluid can be obtained as a mixture of a monatomic gas with a polyatomic one. Here, general principles for choosing such a mixture are discussed, and estimates are given for the savings in size and scale which may be expected (compared to a conventional tunnel), following earlier work of Chapman[2].

BASIC RELATIONS

The relevant basic formulae for thermodynamic properties of binary gas mixtures are given, eg by Chapman[2]. The mixture molecular mass m is

$$m = x_1 m_1 + x_2 m_2, \qquad \qquad \cdots \quad (1)$$

where m_i is the molecular mass of species i and x_i its mole-fraction in the mixture. Note that $x_1 + x_2 = 1$. The mixture specific heat per mole at constant pressure, C_p, is given in terms of pure-gas specific heats C_{p_i} by

$$C_p = x_1 C_{p_1} + x_2 C_{p_2} \qquad \qquad \cdots \quad (2)$$

Here index 1 refers to the monatomic, and 2 to the polyatomic, species. The specific heat at constant volume, C_v, is related to C_p by

$$C_v = C_p - R, \qquad \qquad \cdots \quad (3)$$

where R is the universal gas constant. $R = 1\cdot987$ cal/mole $^\circ K$, and the specific heat ratio γ is

$$\gamma = C_p / C_v. \qquad \qquad \cdots \quad (4)$$

For a binary mixture, γ is given by

$$\gamma = \frac{x_1 C_{p_1} + x_2 C_{p_2}}{x_1 (C_{p_1} - R) + x_2 (C_{p_2} - R)} \qquad \cdots \quad (5)$$

For air, $\gamma = 1\cdot4$. Heavy polyatomic gases, in general, have $\gamma <$

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$1\cdot4$, while for monatomic gases $\gamma = 5/3 > 1\cdot4$. A gas mixture with $\gamma = 1\cdot4$ can therefore be obtained as a binary mixture of a monatomic with a polyatomic gas.

The viscosity μ of a gas mixture can be calculated, with acceptable accuracy, from an approximate relation due to Wilke[3]:

$$\mu = \mu_1 A_1^{-1} + \mu_2 A_2^{-1} \qquad \qquad \cdots \quad (6)$$

$$A_1 = 1 + \frac{\sqrt{2}[1 + (\mu_1/\mu_2)^{1/2}\,(m_2/m_1)^{1/4}]^2}{4(x_1/x_2)\,[1 + (m_1/m_2)]^{1/2}}$$

where μ_i is the pure-gas viscosity of species i; A_2 is obtained by interchanging $1 \longleftrightarrow 2$ in the expression for A_1.

Formulae giving the fractional power reduction $\overline{HP}$ and fractional scale reduction $\overline{L}$ obtained for heavy-gas wind tunnels relative to their air counterparts are given eg by Chapman[2]. The present study compares power and scale between heavy-gas and air wind tunnels operating at the same temperature and pressure in the test section, to a given Reynolds number and Mach number. For this situation the power required for the heavy-gas tunnel is reduced, compared to that for air, by the factor

$$\overline{HP} = \frac{(\mu/\mu_{air})^2}{(m/m_{air})^{3/2}}, \qquad \qquad \cdots \quad (7)$$

and the comparable reduction factor for linear scale size is

$$\overline{L} = \frac{(\mu/\mu_{air})}{(m/m_{air})^{1/2}} \qquad \qquad \cdots \quad (8)$$

PROPERTIES OF HEAVY GASES

1. Monatomic Gases

The heavy monatomic gases considered here are argon (mass 40 amu, viscosity 210 μp at 273°K) and xenon (mass 131 amu, viscosity 210 μp at 273°K). Krypton (mass 84 amu) is a less interesting alternative (see Ref. (4), and the final comments herein), because of its higher viscosity, and high cost compared to argon.

2. Polyatomic Gases

Although a comprehensive survey of polyatomic gases was not undertaken, some 270 compounds which are known to be gaseous at temperatures $\leq 313^\circ$K, and with molecular weight
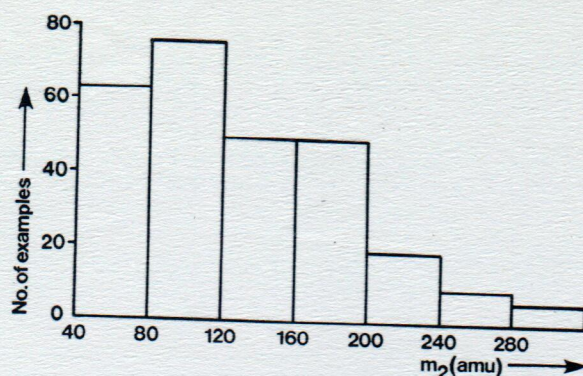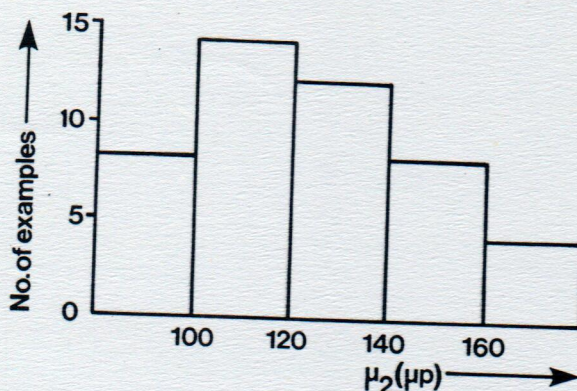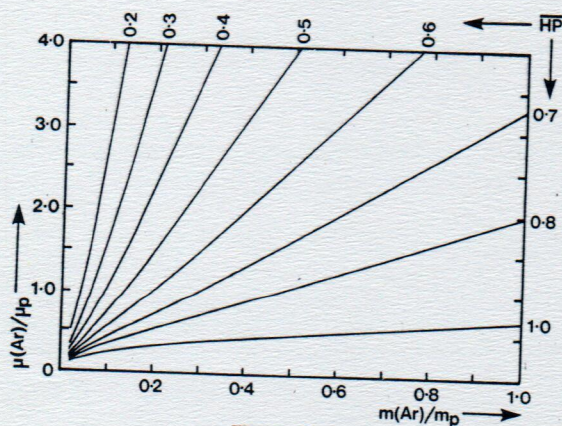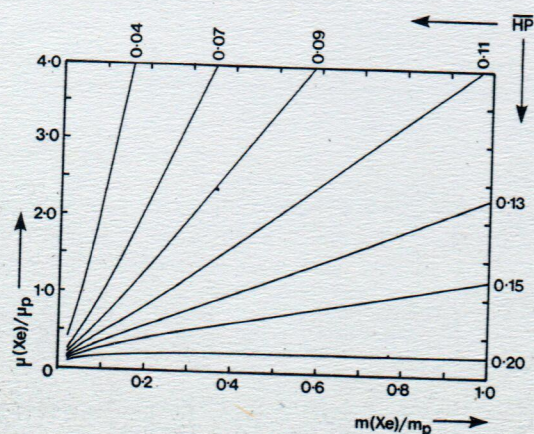
Figure 1.

Figure 2.

Figure 3(a).

Figure 3(b).

$m_2 > 40$ amu, were considered. The distribution of molecular weights for these gases is shown in Fig. 1. Viscosities μ_2 at 273°K were known or estimated for 47 of these gases; the viscosity-distribution is shown in Fig. 2.

Specific heats at or near room temperature were available for 81 of the polyatomic gases considered. A rough correlation exists between the mass m_2 and specific heat C_{p_2} of a polyatomic gas, which may be described by the formula[2]

$$C_{p_2} = Am_2 + B, \qquad \qquad \qquad \cdots \quad (9)$$

where $\{7\cdot64 \times 10^{-2}$ cal/mol °K $\leq A \leq 8\cdot55 \times 10^{-2}$ cal/mol °K$\}$ and $\{0\cdot408$ cal/mol °K $\leq B \leq 16\cdot9$ cal/mol °K$\}$. Specific heats for these gases range from 10 to 38 cal/mol °K.

RESULTS

The way in which the power-saving factor $\overline{HP}$ depends on the mass (m_p) and viscosity (μ_p) of a polyatomic gas, when mixed with argon to a polyatomic mole-fraction of 0·1, is shown in Fig. 3a. This proportion gives $\gamma = 1\cdot4$ when C_{p_2} has the (typical) value 24·8 cal/mol °K. The results follow from equations (6) and (7). Figure 3(b) shows similar results with argon replaced by xenon. Analogous results for the scale-reduction factor $\overline{L}$, following from equations (6) and (8), are shown in Fig. 4(a) (argon mixtures) and Fig. 4(b) (xenon mixtures).

One may instead consider a polyatomic gas with typical (low) viscosity $\mu_p = 110$ μp, and deduce the dependence of power and scale reduction factors on its mass m_p and specific heat C_{p_2}. This dependence of $\overline{HP}$ for argon mixtures is shown in Fig. 5(a) and for xenon mixtures in Fig. 5(b). Existing gases have specific heats falling primarily within the two dashed lines, according to equation (9). Analogous results for $\overline{L}$ are shown in Fig. 6(a) (argon mixtures) and Fig. 6(b) (xenon mixtures).

DISCUSSION

1. Choice of Monatomic Component

Comparisons of the performance of argon mixtures (Figs. 3-6(a)) with xenon mixtures (Figs. 3-6(b)) show the very great advantages, particularly in power-reduction, associated with the use of xenon. These advantages must be weighed against the scarcity and higher cost of xenon, disadvantages which are partly-offset by the smaller volume of gas needed to drive a xenon wind tunnel.

2. Choice of Polyatomic Component

Figures 5 and 6 suggest a different strategy for choosing the polyatomic component, depending on which monatomic component is used. For argon mixtures, the best polyatomic gas appears to be one otherwise suitable, with specific heat as low as possible, $m_p \approx 100 \pm 40$ amu, and $\mu_p \lesssim 110$ μp. Of the gases considered[4], the most suitable was CH_2F_2 (Freon 32), with $m_p = 52$ amu, $\mu_p = 93$ μp at 273°K, and $C_{p_2} = 10\cdot25$ cal/mol °K at 298°K. This gas is far from the theoretical optimum, however, and a significantly better choice is possible in principle.

The performance of xenon mixtures is much less sensitive to the mass and specific heat of the polyatomic component. Figures 5 and 6 suggest that the best polyatomic gas should have $m_p \approx 160$ amu, for the lowest scale factor, or $m_p \approx 200$ ± 40 amu for the best power saving (with viscosity and specific heat as low as possible). Of the gases considered[4], the best was $CBrClF_2$ (Freon 12B1), with $m_p = 165\cdot5$ amu, $\mu_p = 121$ μp at
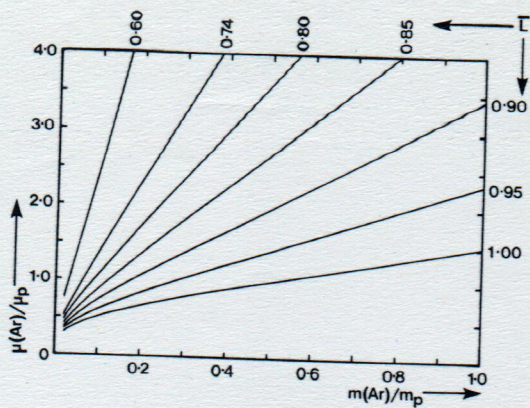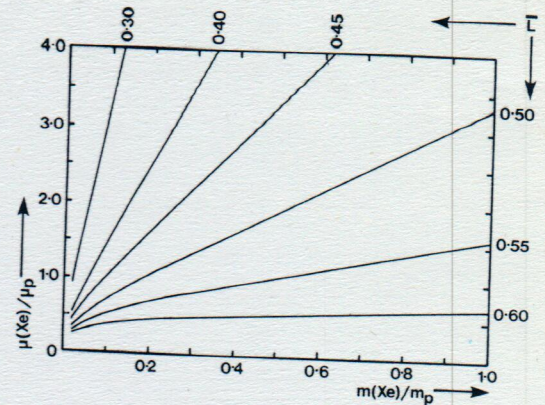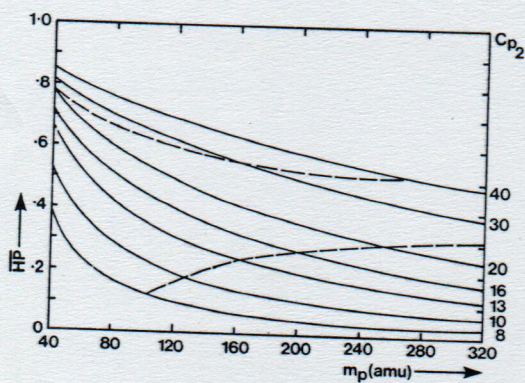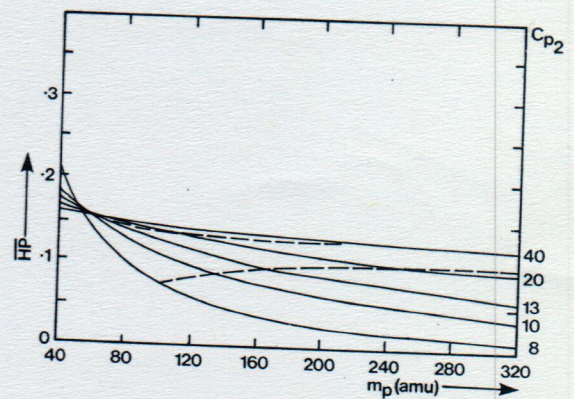
Figure 4(a).

Figure 4(b).

Figure 5(a).

Figure 5(b).
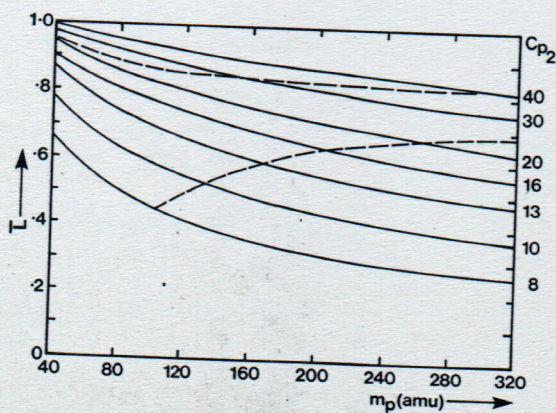
Figure 6(a).
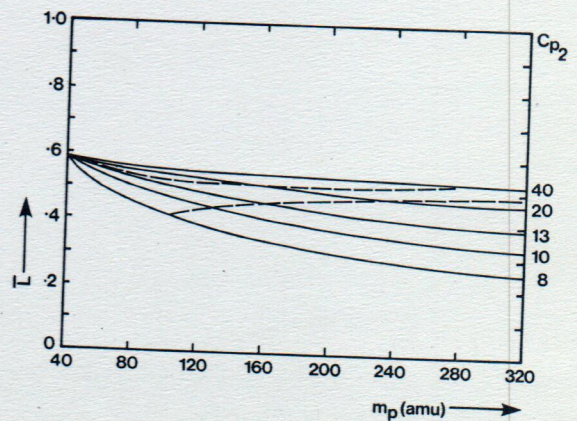
Figure 6(b).

Table 1

Test Temperature	Gas Mix	$\overline{HP}$	$\overline{L}$	Cost-Ratio, Monatomic Gas[5]
298°K	Ar-CH$_2$F$_2$	0·38	0·69	1
	Xe-CBrClF$_2$	0·12	0·51	5·7
230°K	Ar-CH$_2$F$_2$	0·32	0·63	1
	Xe-CBrClF$_2$	0·11	0·50	7·1

273°K, and C_{p_2} = 17·8 cal/mol °K at 298°K. For xenon mixtures, this gas seems representative of the best choices one may expect.

3. Comparison of 'best' wind-tunnel gases

A summary of results for the 'best' wind-tunnel mixtures of the previous section is given in Table 1.

(Krypton mixtures[4] give a power-saving factor roughly $^2\!/_3$ that of argon, and a nearly-equal scale factor, at a cost-ratio of four compared to argon). Both polyatomic gases in Table 1 were considered in Chapman's original study[2]. As discussed above, it would be possible in principle to improve the performance of argon mixtures by using a suitable new gas with the properties specified.

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