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SEPARATION OF A GAS MIXTURE IN CURVED SUPERSONIC FLOW*

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Abstract—The separation effects in a helium–argon mixture accelerated to supersonic speeds in a centred wave flow are investigated experimentally. The strong influence of the sampling probe is discussed and a method is developed for the estimation of the real separation effect from the test data. Within the range of the present experiments the concentration gradients are considerably increased by a decrease in settling chamber pressure and by an increase in degree of expansion. The scale of the accelerating nozzle has a marked influence on the concentration profile

NOMENCLATURE

a_o,	stagnation speed of sound;
h,	nozzle throat width;
M,	Mach number;
$M_2, M_3 M_6$,	survey lines;
n,	light gas component mole fraction;
n_o,	value of n in settling chamber;
n',	experimentally determined mole fraction, before corrections;
Δn,	constant shift of mole fraction line (see equation 3);
p_o,	settling chamber pressure;
p_o',	Pitot pressure;
p_b,	pressure in vacuum chamber, far from nozzle;
p_a, p_α,	diaphragm gauge and ionization gauge outputs, respectively;
Re,	Reynolds number;
s,	distance from corner to centre of probe tip cross-section;
s_o,	length of survey line, corrected for boundary-layer displacement thickness;
α, β, θ,	angles defined in Fig. 4;
γ,	ratio of specific heats;
ν,	kinematic viscosity.

* This study was undertaken by the author at the Gas Dynamics Laboratory of the Department of Aerospace and Mechanical Sciences, Princeton University, while on a sabbatical visit.

INTRODUCTION

SINCE the early days of development of the Kinetic Theory of Gases it has been realized that the tendency of levelling out of concentration differences in a gas mixture by diffusion can be counteracted by three distinct factors: the existence of a pressure gradient, of a temperature gradient or of a force field acting on the gas molecules. The net diffusion flux across any surface in the flow field is a result of the interaction between these three factors and the regular diffusion due to concentration gradient.

Great local pressure gradients arise in a fluid flow wherever the streamlines are strongly curved, and they increase with the second power of speed. It is therefore conceivable that quite strong pressure gradients could be established in a fluid by accelerating it to a supersonic speed and then causing it to turn along streamlines of small radii of curvature.

Such flows of gas mixtures have been observed in recent years by a number of investigators [1–5]. The type of flow utilized in most of these experiments was the efflux from a circular orifice into a region of low pressure. Though easy to produce, such flows are quite complicated from the point of view of theoretical analysis.

It seems advisable to obtain experimental results on separation effects in flows of a basically simple form from the theoretical point of view. Such experimental data should provide

useful material for comparison with future theoretical results.

A basically simple supersonic flow pattern with curved streamlines is offered by the steady simple wave solution [6, 7]. This is a steady two-dimensional flow in which changes in flow direction and pressure are propagated along one family of characteristic lines only, which are straight lines.

It is quite easy to design and generate such flows. Considering an expansion of a supersonic stream along a curved wall, an opposite wall can be designed so as to cancel any wave originating at the first wall. And since such flows can be treated analytically in closed form, they offer a suitable pattern for the basic study of separation effects due to pressure and temperature gradients.

In the present investigation centred simple wave flows were generated with mixtures of monoatomic gases and the gas composition of samples drawn from different regions of the flow field was determined experimentally. The results revealed both the expected concentration gradients due to the streamline curvature of the main flow and a strong separating effect due to the disturbance introduced by the sampling probe.

THE EXPERIMENTAL APPARATUS

Figure 1 shows a diagram of the experimental set up. A mixture of two gases is fed from pressure tank A through a pressure reducer and a needle valve into settling chamber B. From there it is accelerated through nozzle C into vacuum chamber D. The converging part of the nozzle is bounded by four plane surfaces inclined at an angle of 15° to the throat section. The diverging part of the nozzle is a passage of rectangular cross-sections of constant depth, bounded by two plane parallel side walls and by two curved walls, so designed as to maintain a simple wave expansion flow between them. In order to obtain streamline curvatures as great as possible, the convex curved wall was replaced by a sharp edged corner. The supersonic flow was thus forced to turn around a corner and the opposite concave wall was designed so as to cancel the expansion waves emerging from the corner. The resulting supersonic flow configuration is a simple centred wave.

The concave wall profile was designed by the method of Characteristics [6, 7], and a boundary layer correction has been introduced following the method of Cohen and Reshotko [8].

Two interchangeable concave walls were used in the experiments, defining centred simple waves for monoatomic gas flow ($\gamma = 5/3$), one with a throat width $h = 0{\cdot}100$ in and one with $h = 0{\cdot}025$ in. They will be referred to as the 0·100 in nozzle and the 0·025 in nozzle, respectively. Both wall contours were cut off at a point corresponding to a theoretical flow expansion to $M = 3$.

The distance between the two parallel walls,

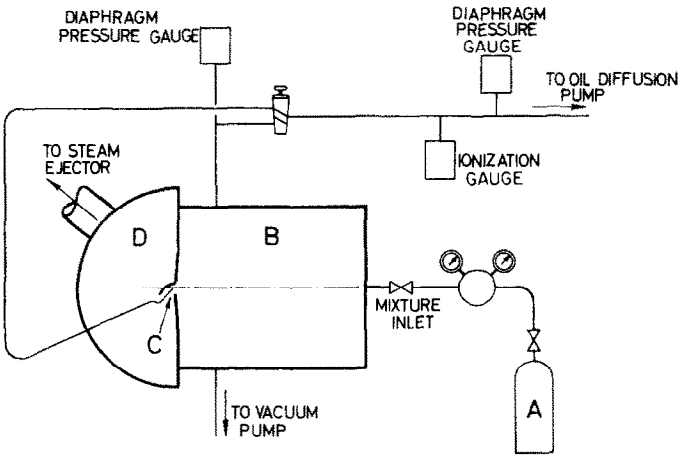

FIG. 1. Schematic representation of experiment.

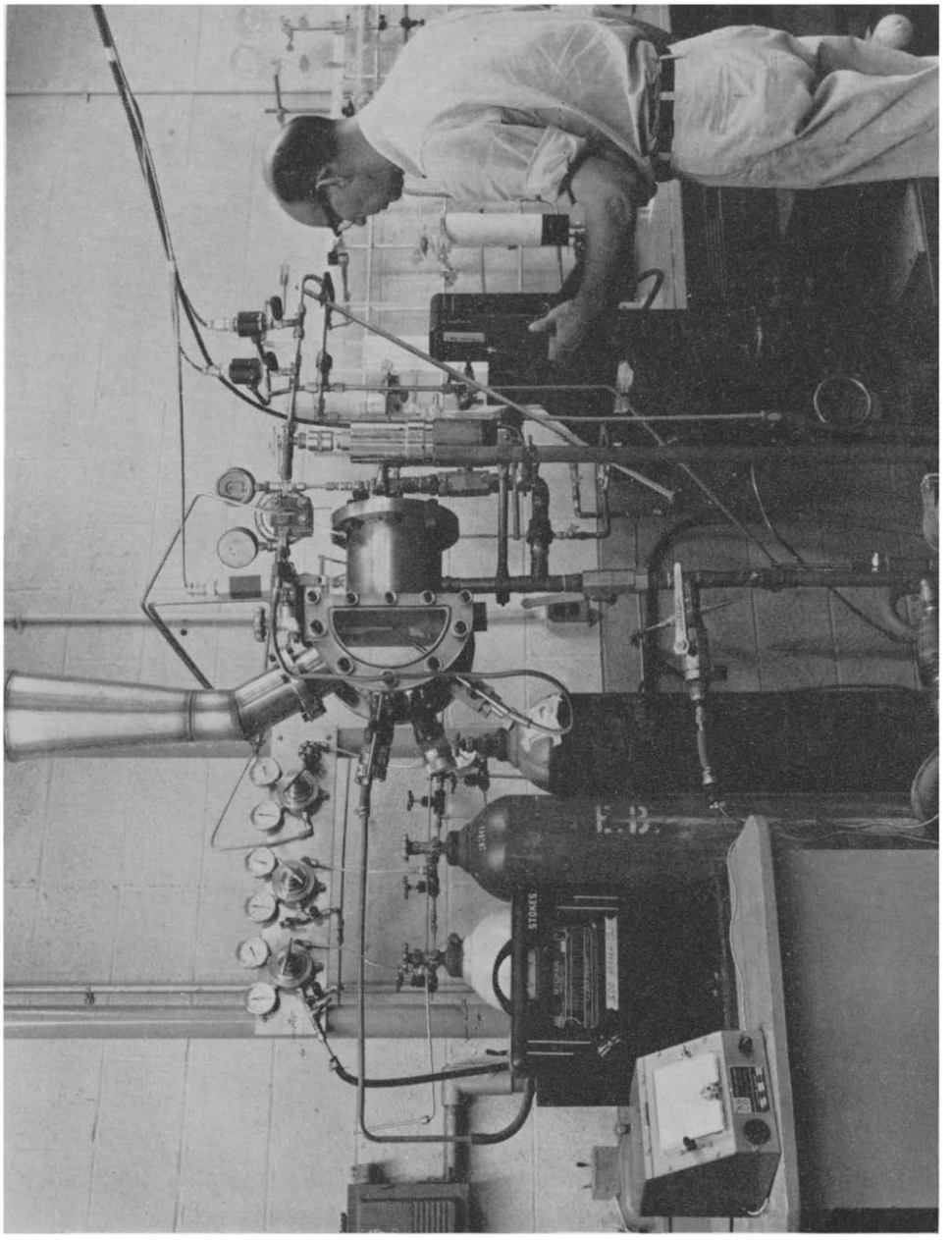

FIG. 2. Photograph of experimental installation.

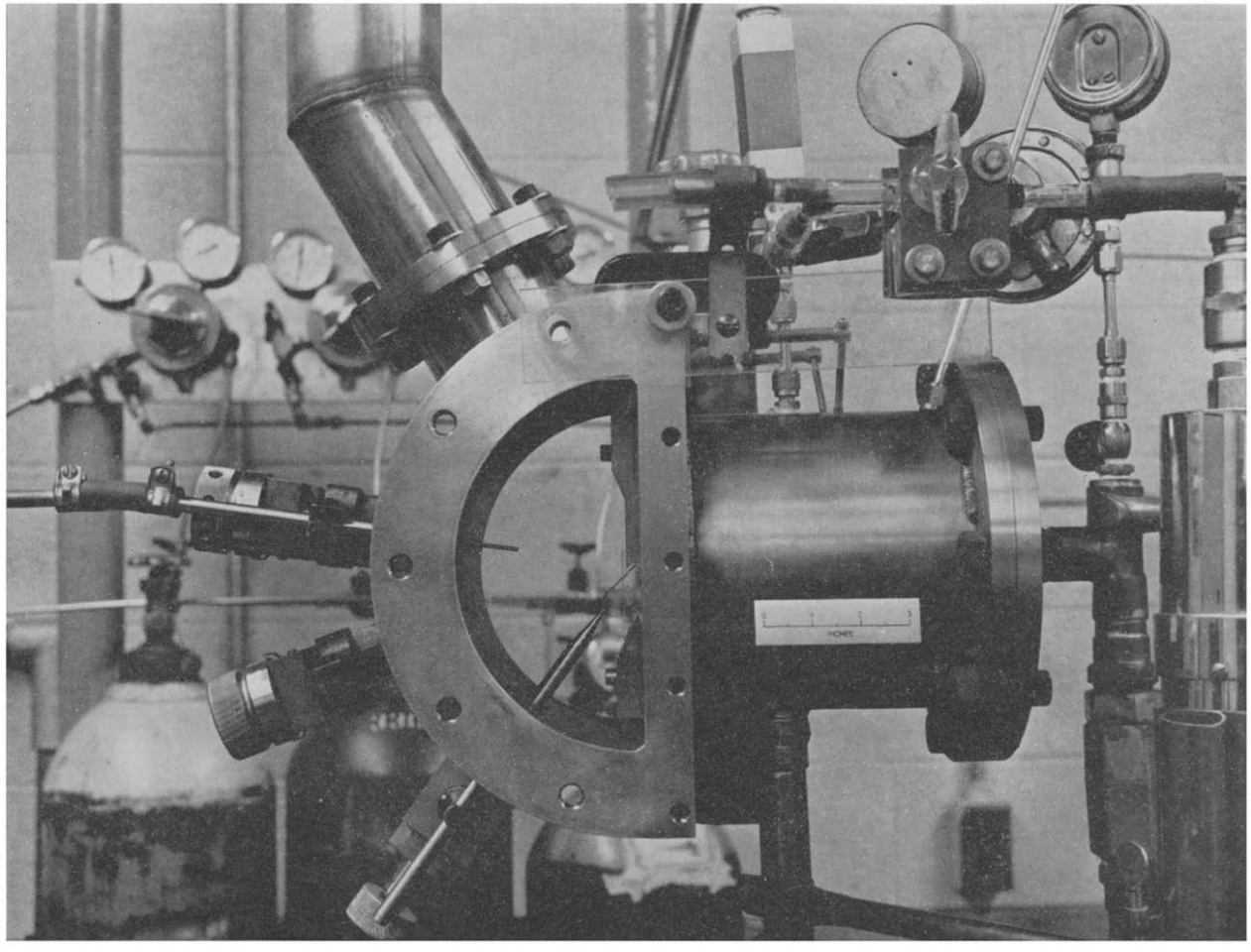

FIG. 3. Close-up view of wind tunnel.

defining the nozzle depth, was 1 inch in all the experiments. These two walls, as well as the plane side walls of chamber D, were fabricated of Plexiglass, to facilitate inspection of probe positioning.

The boundary layer correction was effected for

$$R_e = \frac{a_o h}{\nu} = 1600,$$

where a_o and ν are the speed of sound and kinematic viscosity in the settling chamber. This corresponds to settling chamber pressures $p_o = 20$ mm Hg for the 0·100 in nozzle, and $p_o = 80$ mm Hg for the 0·025 in nozzle. The settling chamber pressure range

$$2{\cdot}5 \leqslant p_o \leqslant 13 \text{ mm Hg}$$

turned out subsequently to be more relevant, so that most of the experiments were performed with an insufficient boundary-layer correction. But up to the relatively low Mach numbers of this investigation the boundary-layer correction is quite small, so that the basic flow pattern was only slightly affected by the deviation of Reynolds number from its design value. This has been verified by total head surveys along the characteristic lines corresponding to design Mach numbers $M = 2$ and $M = 3$, which will be discussed subsequently (see Fig. 5).

Figure 2 is a photograph of the experimental arrangement. A close up view of the tunnel is shown in Fig. 3.

The flow rate through the system and the low pressure in chamber D were maintained constant by evacuation of the incoming gas mixture by a powerful four stage steam ejector. The steam ejector was capable of maintaining a flow of air of 10 lb/h at a pressure $p_b = 3 \times 10^{-1}$ mm Hg in the vacuum chamber.

MEASURING TECHNIQUE

For a flow of a single component gas the straight lines through the sharp edge of the corner are characteristic lines. Constant values of pressure, Mach number and flow direction are predicted theoretically along them.

In the actual flow of a gas mixture the true characteristic lines are somewhat curved, due to the variation of gas concentration along them. This deviation of the characteristics from straight lines is a secondary effect that could be neglected to a first approximation.

Samples of gas mixture were extracted from points along such straight lines by specially designed probes. Each probe could be moved by a micrometer screw so that the centre of its tip section should be displaced along a straight line through the corner. The axis of the probe tip was in line with the local flow direction.

The probes had a tip formed by a thin flattened hypodermic tubing, with an external width of 0·043 in, an external thickness of 0·020 in and a tube wall thickness of 0·005 in. The tip edge was carefully sharpened.

Provision was taken to allow sampling along three straight lines, corresponding to the characteristic lines along which $M = 2$, 3, and 6, respectively, in a single component gas flow. These lines will be referred to as M_2, M_3 and M_6 survey lines. The experiments discussed below were performed with sampling along lines M_2 and M_3 only.

The method of determination of molar concentration of a sample of binary gas mixture was based on the sensitivity of an Ionization vacuum gauge to the composition of sampled gas. In such a gauge the molecules of gas are ionized and the ions are collected, fed into a preamplifier and then into a sensitive electrometer circuit for direct reading or recording of output.

For samples of a given gas species the number of ions produced, and hence the output, is proportional to pressure. This linear response to pressure is an important feature of the gauge.

The gauge responds differently, however, to different gases at the same pressure, and requires therefore a separate calibration for each gas.

This selective response of the ionization gauge to different gas molecules can be exploited for the determination of gas composition of a binary gas mixture.

Let the abscissa in Fig. 4 represent the pressure p_a of a gas sample, in some arbitrary units, as determined by a pressure gauge whose response does not depend on the nature of the gas. Let the ordinate represent the pressure reading p_α for the same sample, as determined

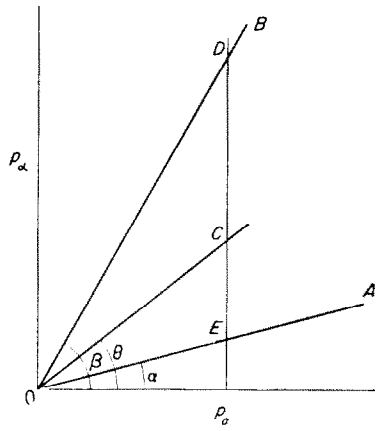

FIG. 4. Mole fraction determination by ionization gauge.

by the ionization gauge. Measurements of pressure for a gas of fixed composition by the two gauges will be represented in this diagram by a straight line through the origin.

If OA and OB are two such calibration lines for the pure gases A and B, the corresponding measurement for a given sample of mixture of the two gases may be represented by some point C in the region between lines OA and OB. Assuming that the pressure is low enough for the mixture to behave as a perfect gas, it can easily be shown that the mole fraction n of the light gas A in the sample is given by

$$n = \frac{\overline{DC}}{\overline{DE}} = \frac{\tan\beta - \tan\theta}{\tan\beta - \tan\alpha} \tag{1}$$

where E and D are the intersections of lines OA and OB with a vertical line through point C and α, β and θ are the angles between the horizontal axis and lines OA, OB and OC, respectively.

In the present experiments true pressure readings, obtained with a variable inductance diaphragm gauge, were compared with the output of a Model 530 Alphatron Ionization gauge. The diaphragm gauge was calibrated against a high precision McLeod gauge.

The gas sample was drawn from a point in the flow field through the sampling probe by a separate oil diffusion vacuum pump. The tube leading from probe to vacuum pump was connected to the diaphragm gauge and to the Alphatron gauge at two neighbouring positions.

A separate diaphragm gauge measured the settling chamber pressure p_o, while the back pressure p_b in the vacuum chamber at a considerable distance from the supersonic flow region was sensed by a tube connected to a Stokes–McLeod vacuum gauge.

For each position of the probe tip along the characteristic line enough time was allowed for all the gauges to come to equilibrium. The outputs from the diaphragm gauges and from the Alphatron gauge were then fed in succession into an electronic counter by a multiple switch and its readings recorded. The back pressure in the vacuum chamber and the probe position were simultaneously recorded.

The same sampling probes and traversing mechanism were also used in order to determine the Mach number distribution along survey lines M_2 and M_3. But for this purpose the oil diffusion vacuum pump was cut off from the sampling probe, so that the pressure measured by the diaphragm gauge represented the stagnation pressure p_o' behind the normal shock wave formed in front of the probe tip. Assuming that the only total head loss along the streamline leading to the probe stagnation point occurs across the normal shock wave, the supersonic Mach number M in front of the probe tip can be determined by the following equation:

$$\frac{p_o}{p_o'} = \left(\frac{2\gamma}{\gamma+1}M^2 - \frac{\gamma-1}{\gamma+1}\right)^{1/(\gamma-1)} \left(\frac{(\gamma-1)M^2+2}{(\gamma+1)M^2}\right)^{\gamma/(\gamma-1)} \tag{2}$$

The above assumption is incorrect for streamlines within the boundary layer near a solid wall. At a point within the boundary layer the measured stagnation pressure p_o' may be much lower than the corresponding value at neighbouring points in the main stream along the same characteristic line. Thus the approach of the boundary layer is clearly indicated by a sharp decrease in measured p_o' values. This would correspond with a fictitious rapid increase in M, as calculated by equation (2). The true value of M decreases, of course, as we approach the solid wall, but it cannot be determined by the procedure described above.

EXPERIMENTAL RESULTS

(a) *Mach number distribution along* M_2 *and* M_3

In the total head surveys rather long time intervals were required before the gauges approached equilibrium. This is due to the high resistance to flow offered by the thin probe tip and to the relatively big volume of gauge and connecting tubing. It was therefore difficult to obtain many accurate total head readings along a characteristic line during the 20 min run duration.

The limited amount of data that were obtained (Fig. 5) showed the expected Mach number distribution along line M_3, which in some cases deviated by less than 4 per cent from the nominal value over 95 per cent of the characteristic line.

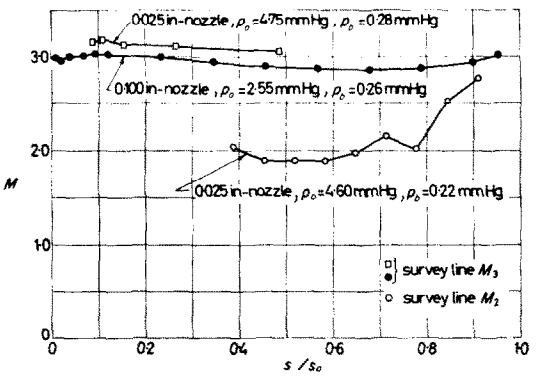

FIG. 5. Mach number distribution from total head surveys.

The Mach number distributions evaluated from p_o' measurements along line M_2 were less satisfactory, deviating by as much as ± 8 per cent from the nominal value over the region covered by the measurements. Figure 5 includes some comparative results of the total head surveys for the 0·100 in nozzle and the 0·025 in nozzle. The bigger nozzle has a much more satisfactory evaluated Mach number distribution. This may be an indication of flow disturbance produced by the presence of the probe. The same probe produces a stronger flow disturbance in the smaller nozzle.

(b) *Concentration distributions*

Figure 6 represents some typical data obtained from a run of helium–argon mixture through the 0·100 in nozzle. The light-component mole fraction in the undisturbed mixture was $n_o = 0{\cdot}62$, settling chamber pressure $p_o = 8{\cdot}35$ mm Hg and back pressure in vacuum chamber $p_b = 0{\cdot}27$ mm Hg.

The lines marked HE, A and Mixture are calibration lines of the Alphatron gauge for each of the gas components and for the undisturbed mixture, respectively. These lines were determined before the wind tunnel run by maintaining the pressure in the settling chamber at controlled low values and by sampling gas directly from the settling chamber to the Alphatron and diaphragm gauges, without acceleration through the nozzle.

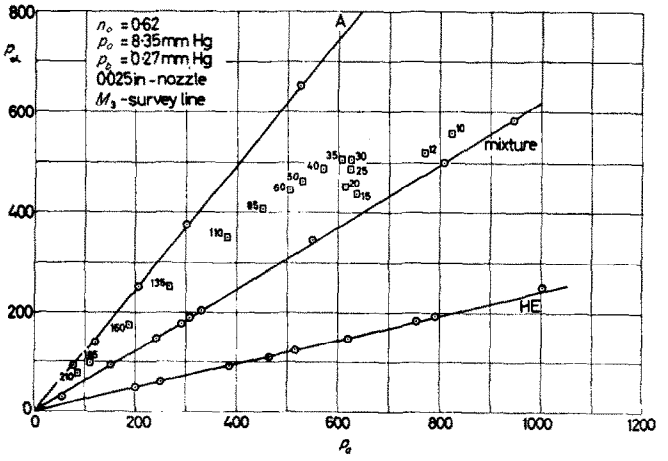

FIG. 6. Typical p_{ai} vs. p_a polar.

The experimental points marked by squares were taken along survey line M_3. The numbers near the experimental points indicate the distance from centre of probe tip cross section to corner, in thousandths of an inch. It is observed that when the probe is moved from the corner towards the concave outer wall the line connecting the origin of co-ordinates to the experimental point rotates in a direction from the helium calibration line to the argon calibration line, indicating a sharp decrease in helium concentration over the first few 10^{-2} in.

The whole line of experimental points appears however to be turned towards the argon line, so that the mixture flowing across survey line M_3 seems to be on the whole richer in argon than the original mixture in the settling chamber.

Since before the run the whole system was baked out, evacuated to a pressure of less than 10^{-3} mm Hg for over 12 h and carefully checked for leaks, this apparent distortion cannot be due to any inflow of matter from outside or degassing within the system.

In order to check conclusively whether this apparent surplus of heavy gas component may not be due to an influx of flow from an extraneous source, a few tests were performed by feeding pure argon to the settling chamber and accelerating it through the 0·025 in nozzle. The settling chamber pressure was varied in these runs over the range $4{\cdot}7 \leqslant p_o \leqslant 16{\cdot}3$ mm Hg. All the p_α vs. p_a points determined by sampling the supersonic flow field fell nicely on the argon calibration line, within the experimental error.

It is concluded that the deflection of p_α vs. p_a points towards the heavy gas component calibration line, that was consistently found in runs with a gas mixture, must be due to a strong local separation effect of the sampling probe itself.

Though the suction through the probe is maintained by a separate oil diffusion pump capable of producing a high vacuum, the friction of the sampled flow within the thin tubing of the probe tip causes choking at the probe intake. A detached shock wave is formed in the supersonic stream in front of the probe tip and some of the subsonic flow behind the shock wave, which was originally directed towards the probe entrance, is spilled over, following highly curved streamlines. One should expect an intense local centrifugal field which causes the probe to collect preferentially the heavier gas component.

Such a probe effect was observed in the early work of Becker and Bier [9], and was studied by Reis and Fenn [10].

If the probe were moving in a homogeneous flow field and far from solid walls, its separation effect would result in a *constant* shift of the measured high component mole fraction from its actual value n in the absence of a probe. This is not the case in our experiments. The probe effect is further complicated by the following circumstances:

(a) When the probe penetrates into a boundary layer, the flow Mach number in front of it decreases. The above mentioned probe effect is thereby weakened, and this must result in an increase in observed n' values toward the concave nozzle wall. Such an increase in n' was consistently observed in the present experiments. It was accompanied by a rapid decrease in pressure p_a, clearly indicating the presence of a boundary layer.

(b) When the probe approaches closely the sharp corner its presence destroys the centred wave flow pattern. This is evidenced by the irregular variation of p_a in this vicinity. Therefore we cannot expect to obtain reliable concentration data in the immediate vicinity of the corner by the sampling technique. One could, at most, extrapolate concentration data measured in the main flow field, at a distance from the corner greater than one probe thickness.

In view of these observations the following standard procedure was adopted to correct the data for probe effects:

1. From the experimentally obtained plot of p_α vs. p_a along a characteristic line the apparent light gas mole fraction n' was calculated by equation (1) and plotted as a function of distances from the corner.

2. This curve contains a nearly horizontal section in the central flow region. The apparent sharp increase in n' towards the concave wall, which represents the weakening of probe separation effect in the boundary layer, was replaced by extrapolating the central section of the curve by a horizontal line, which is terminated at a

distance from the wall equal to the boundary-layer displacement thickness.

3. Moving along the characteristic line towards the corner, n' first increases gradually, indicating the separating effect of the simple wave flow. In the absence of a probe one would expect n' to increase continually right up to the corner. The experimental curve n' vs. s is therefore extrapolated from the central flow region towards the corner following a tangent of highest slope (Fig. 7).

4. The resulting curve is biased by an approximately constant probe separating effect, which is eliminated by increasing the ordinates by a constant amount $-\Delta n$, so as to satisfy approximately the conservation of flow of light gas component across the characteristic line. $-\Delta n$ is determined by the equation

$$\frac{1}{s_o}\int_o^{s_o}(n' - \Delta n)\,\mathrm{d}s = n_o \qquad (3)$$

where s_o is the length of the survey line and n_o is the light gas component mole fraction in the settling chamber.

All the data discussed subsequently have been evaluated and interpreted in this manner. The corresponding $-\Delta n$ adjustments are indicated on each mole fraction distribution curve.

Mach number effect

In a simple wave expansion the velocity increases monotonically along a streamline. But the streamline radius of curvature first decreases, reaches a minimum and then increases to infinity. In line with these facts it is to be expected that at small values of Mach number the separation effect due to the curved flow pattern should be intensified with the degree of expansion; the concentration gradient should be strongest along a characteristic line corresponding to some finite Mach number and it should then be gradually destroyed at higher Mach numbers by ordinary diffusion.

In the present series of experiments the gas mixture separation along the M_3-line was consistently stronger than along the M_2-line, under otherwise identical conditions. Figure 8 shows a comparison of helium mole fraction distributions for a HE–A mixture with initial conditions $n_o = 0{\cdot}61$, $p_o = 3{\cdot}45$ mm Hg, expanding through the 0·025 in nozzle to a vacuum chamber back pressure

$$p_b = 0{\cdot}260 \text{ mm Hg.}$$

The sampling was carried out along the M_2 and M_3 survey lines. The Mach number for which maximum separation is reached is apparently higher than 3.

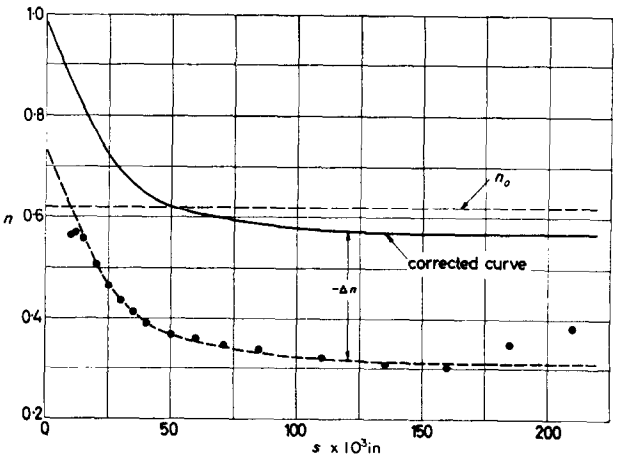

FIG. 7. Correction of experimental results for probe effect.

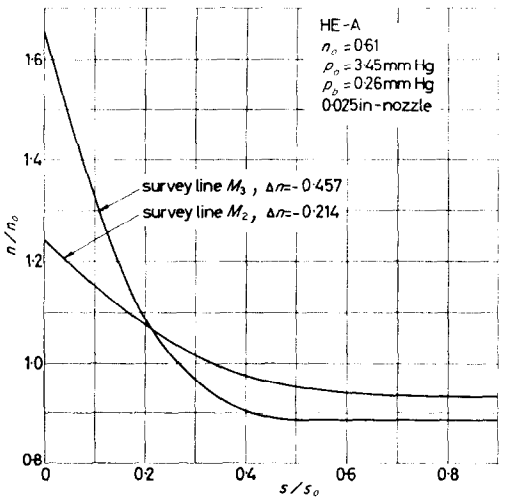

FIG. 8. Effect of degree of expansion on separation.

Effect of settling chamber pressure

Figure 9 shows a comparison of helium mole fraction distributions along line M_3 for flows of HE–A mixture through the 0·025 in nozzle with different settling chamber pressures p_o. The initial gas composition and the vacuum chamber back pressure were maintained within a close range.

It is observed that the variation in light gas mole fraction along the line of survey increases progressively with decrease in settling chamber pressure in the range

$$3{\cdot}45 \leqslant p_o \leqslant 11{\cdot}40 \text{ mm Hg.}$$

In experiments at still lower values of p_o it was impossible to obtain supersonic flow along the whole M_3-line for the given back pressure. This became apparent from a total head survey of the flow along M_3-line at $p_o = 2{\cdot}45$ mm Hg. Under this low p_o condition the gas composition distribution followed the usual pattern in the vicinity of the corner, n' decreasing strongly with increasing distance from the corner. But at larger distances s the shallow plateau in the n' curve did not appear. n' increased with s, instead, in a rather irregular manner, and it was impossible to evaluate a probe correction in this case.

Effect of nozzle scale

On Fig. 10 two runs performed with a HE–A mixture through the 0·100 in nozzle are compared with two runs with the same mixture through the 0·025 in nozzle. In all four runs of Fig. 10 the helium mole fraction of the undisturbed mixture was $n_o = 0{\cdot}38$ and the samples were taken along the M_3 survey line; the back pressure differed somewhat from run to run, remaining within the range

$$0{\cdot}23 \leqslant p_o \leqslant 0{\cdot}36 \text{ mm Hg.}$$

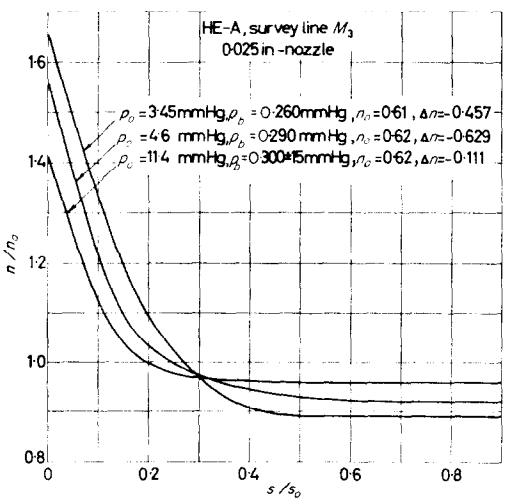

FIG. 9. Effect of p_o on separation.

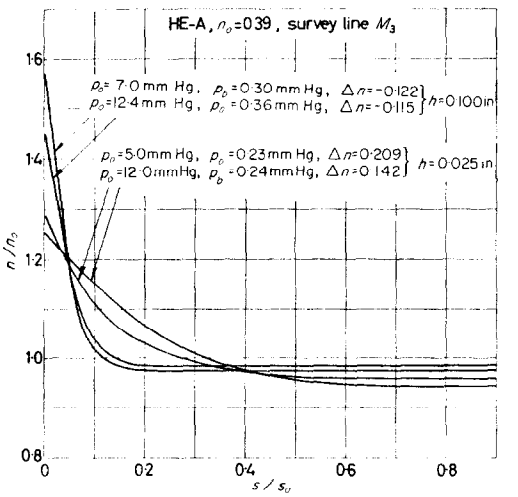

FIG. 10. Effect of nozzle scale.

The pair of runs through each separate nozzle confirms the result exhibited in Fig. 9. The run with the lower p_o-value yields consistently a stronger separation than the high p_o run through the same nozzle. However both runs through the smaller nozzle show a markedly lower effect than the big nozzle runs.

Apparently the curved solid wall opposite the sharp corner has a damping effect on the separation tendency, since it imposes a boundary condition not only on the mean flow velocity vector, but also on the diffusion flux: the particles of each separate species cannot cross its surface.

Effect of n_o

A number of HE–A runs were repeated with different initial helium mole fraction n_o. Figure 11 is a representative comparison between two such runs. The gas separation is apparently effected easier in a mixture rich in light component. This was consistently borne out by similar runs at other settling chamber pressures, as well as in the case of flow through the bigger nozzle.

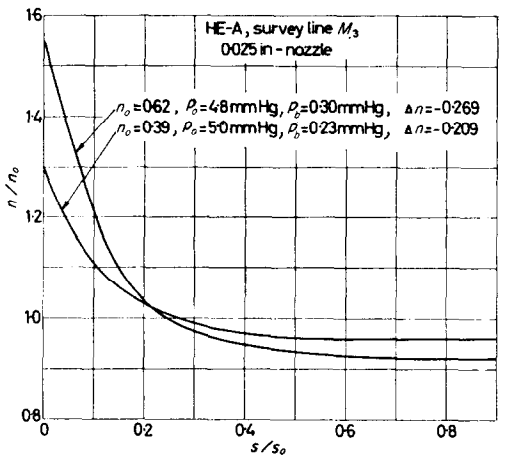

FIG. 11. Effect of initial mole fraction.

CONCLUDING REMARKS

There is some controversy in the literature as to the correct interpretation of the observed separation effects in high speed flow of a gas mixture. Whether it is adequate to view this phenomenon in terms of free molecule flow, as suggested in reference [4], or of continuum flow, depends on the nozzle dimensions and settling chamber pressure, which together determine the Knudsen number of the experiment. Most of the experiments discussed in the literature, including those reported in reference [4], do not fall into the free molecule flow regime.

An analytical approach to the problem of separation of a gas mixture in continuum flow requires the solution of Chapman and Enskog's diffusion equation together with the hydrodynamical equations. With general boundary conditions this is a formidable task even if the ideal flow simplification is applied in the formulation of the hydrodynamic problem. It is hoped that the special case of a simple wave flow, which was closely approximated in this study, will be amenable to theoretical analysis.

Reis and Fenn [10] have justly stressed the fact that the sampling probe establishes in front of itself a shock wave disturbance which is responsible for much of the measured mixture separation effect. In fact a separation tendency should appear in a flow of gas mixture wherever the streamlines are curved and the flow velocity is high, because under these conditions there exists a strong pressure variation in a direction normal to the streamlines. Such big streamline curvatures may be caused either by the geometry of the main flow or by the presence of the sampling device in the flow region. In the experiments reported by Chow [5], where the probe diameter was smaller by an order of magnitude than the nozzle diameter, the probe disturbance must be responsible for the major part of the separation effect. But in the experiments described above the effect of both main flow pattern and of the probe disturbance on separation were clearly evident. And just in those cases in which great variations in concentration along the sampled line were obtained, the required probe correction $-\Delta n$ was highest.

In this connection it should be stressed that the sampling method for determination of separation effects has an inherent difficulty. In order to obtain a very localized sample one is tempted to use a very fine probe. But the shift in measured concentration due to presence of probe is intensified with decrease of probe dimensions. And since the probe effect is at least of the same order of magnitude as the main

investigated effect, it is probably not justified to assume that the effects are linearly additive.

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Résumé—Les effets de séparation dans un mélange d'argon et d'hélium accéléré jusqu'à des vitesses supersoniques dans un écoulement d'ondes simples en éventail ont été étudiés expérimentalement. L'influence importante de la sonde de prélèvement est discutée et une méthode est exposée afin d'estimer l'effet réel de séparation à partir des données expérimentales. Dans le gamme des expériences actuelles les gradients de concentration sont augmentés considérablement par une décroissance de la pression de la chambre de tranquillisation et par une augmentation dans la degré de détente. L'échelle de la tuyère accélératrice a une influence marquée sur le profil de concentration.

Zusammenfassung—Die Trenneffekte in einem Helium–Argongemisch das in einer zentrierten Wellenströmung auf Überschallströmung beschleunigt ist werden experimentell untersucht. Der starke Einfluss der Entnahmesonde wird diskutiert und eine Methode entwickelt, die eine Abschätzung des wirklichen Trenneffekts ermöglicht. Im Bereich der durchgeführten Experimente werden die Konzentrationsgradienten beträchtlich erhöht bei einer Verminderung des Kammerruhedrucks und bei einer Steigerung des Expansionsgrades. Der Massstab der Beschleunigerduse hat einen deutlichen Einfluss auf das Konzentrationsprofil.

Аннотация—Проведено экспериментальное исследование эффектов разделения в смеси гелий-аргон, разогнанной до сверхзвуковой скорости, при течении с центрированной волной. Отмечено влияние зонда. Разработан метод расчета действительногоэффекта разделения по опытным данным. В диалазоне данных экспериментов градиенты концентрации значительно увеличивались вследствие понижения давления в форкамере и увеличения степени расширения. Характерный линейный размер ускоряющего сопла оказывал заметное влияние на профиль концентрации.