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EFFECT OF OPERATING CONDITIONS, PHYSICAL SIZE AND FLUID CHARACTERISTICS ON THE GAS SEPARATION PERFORMANCE OF A LINDERSTROM-LANG VORTEX TUBE

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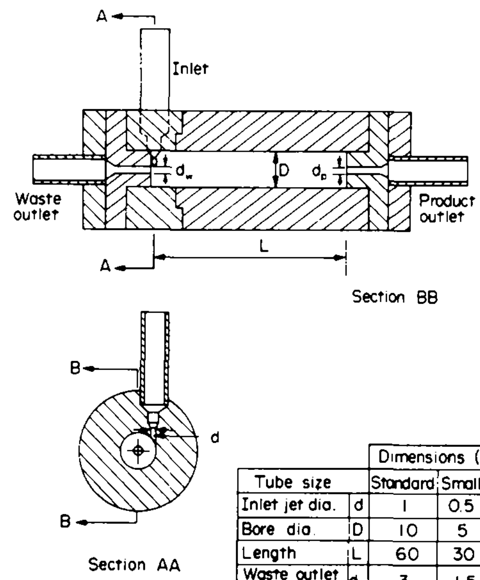
Abstract—Linderstrom-Lang has reported that partial separation of the components of a gas mixture occurs when it is passed through a particular type of vortex tube. The present work confirms this effect and, using several different gas mixtures and several different sizes of tube, shows that there is a critical inlet Reynolds number for maximum separation by this device. A correlation is derived which satisfactorily predicts the performance over a wide range of gas parameters and applied pressures.

NOMENCLATURE

α_{pf}, separation factor for light species between product and feed streams;
γ, ratio of specific heats;
δ, measured concentration difference;
θ, cut, fraction of total flow in product stream;
μ, viscosity;
ρ, density;
A, proportionality constant;
d, inlet jet throat diameter;
M, molecular weight (molar weight);
N, mole fraction of tracer (heavy species);
p, pressure;
Re, Reynolds number;
Sc, Schmidt number;
T, absolute temperature.

Subscripts

e, exit stream condition;
f, feed stream;
0, inlet condition;
p, product stream;
w, waste stream.



Tube size		Dimensions (mm) Standard	Small	Large
Inlet jet dia.	d	1	0.5	2.57
Bore dia.	D	10	5	25.7
Length	L	60	30	154
Waste outlet orifice dia.	d_w	3	1.5	7.7
Product outlet orifice dia.	d_p	2	1	5.14

FIG. 1. Vortex tube.

1. INTRODUCTION

LINDERSTROM-LANG [1, 2] has reported that separation effects occur in gas mixtures in passing through particular types of vortex tube. He investigated various shapes of tube, various combinations of orifice sizes and the effect of "cut" (the relative flow in one outlet orifice). The work described here is based upon one of the vortex tube shapes described in [1] and extends the range of gases and operating conditions in order to find the effect on separation performance. The shape of the tube used is shown on Fig. 1 which also lists the dimensions of three sizes tested. The "standard" size is to the dimensions given in [1] on Fig. 2(b) curve 3/2 III, the "large" tube has all dimensions multiplied by 2.57 and the "small" tube has the dimensions divided by 2.

The experiments were initially intended simply to test the broad postulate that the prime cause of gas species separation is centrifugation by finding the separation performance for gas mixtures of widely different molecular weights and comparing this against a simple model. In carrying out these experiments various other phenomena of interest were found and investigated as far as the equipment available permitted. These include the effects of inlet and outlet pressures.

2. EXPERIMENTAL ARRANGEMENT

The flow rig is shown on Fig. 2. Gas mixtures consisted of a "bulk" gas, which determined the major part of the fluid properties, and a "tracer" gas which was measured to determine the separation perform-

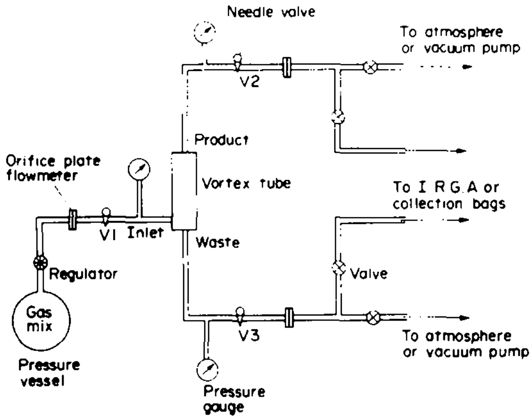


FIG. 2. Flow rig.

ance. The bulk gases were helium, air, nitrogen or argon and the tracer was either nitrous oxide or carbon dioxide. Gas concentration was measured by a Grubb Parsons infrared gas analyser type SB1 which was modified by addition of a phase sensitive measuring system to permit use in a differential mode and so allow measurement of small differences between the two outlet gas streams. The analyser was calibrated with known gas mixtures and could detect differences of 0.1% of concentration level between two streams. It measured a parameter $\delta = N_w - N_p$ where N_w and N_p are the mole fractions of tracer in the waste and product streams respectively. As the tracer was always of higher molecular weight than the bulk gas, positive δ indicates higher light fraction in the product stream. The concentration levels were generally about 10 000 ppm but very wide variations did not appear to affect the results.

Defining cut as

$$\theta = \frac{\text{molar flow in product stream}}{\text{molar flow in feed}}$$

and separation factor (for the light species) as

$$\alpha_{pf} = \frac{\text{relative abundance of light species in product}}{\text{relative abundance of light species in feed}}$$

$$= \frac{1-N_p}{N_p} \cdot \frac{N_f}{1-N_f}$$

then by use of the mass continuity equation

$$N_f = \theta \cdot N_p + (1-\theta) N_w$$

the separation factor is

$$\alpha_{pf} = \frac{1 + \delta \dfrac{1-\theta}{1-N_f}}{1 - \delta \dfrac{1-\theta}{N_f}}.$$

At each set of experimental conditions, gas mixture and applied pressures, the variation of separation factor with cut was determined. Several typical characteristics are shown on Fig. 3 and these are similar in form to those given in [1]. The criterion of performance was taken to be the peak value of α_{pf} achieved. This was chosen rather than the more usual one of separation at a fixed cut because the peakiness of the characteristics and the variability of position of the peak with cut would give widely scattered, unsystematic results at constant cut. The condition may indicate achievement of a particular flow pattern within the vortex. The cut at which the peak appeared was generally at about 0.4 but occasional values down to 0.2 and up to 0.6 were found. It will be noticed that a reversal in the sign of separation occurs at a cut lower than the peak.

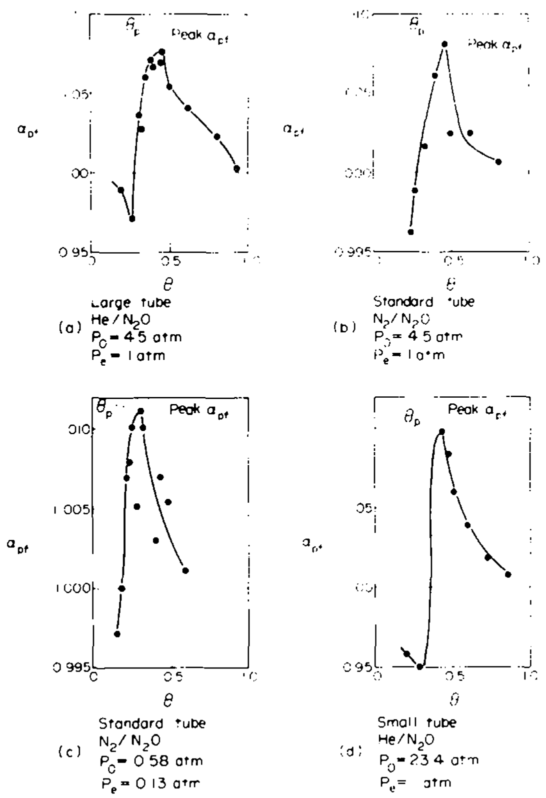


FIG. 3. Typical characteristics: separation vs cut.

3. EFFECT OF INLET CONDITION WITH OUTLETS VENTING TO ATMOSPHERE

The tests reported in [1] for this tube shape were made with air (O_2/N_2) at 4.5 atm inlet and 1 atm outlet and so initially in the present work the effect of inlet conditions was tested with outlet venting to atmosphere. These tests covered four of the bulk gases and the three tube sizes. The overall pressure drop consists of components across the inlet jet, in the vortex itself and over the outlet jets. The inlet jet is predominantly the most restrictive and so will support the main part of the pressure drop until it chokes in sonic condition. After this point, i.e. where the overall pressure ratio is substantially greater than 2, the Reynolds number in the inlet jet may be shown in the usual way for a perfect gas to be:

$$Re = \frac{P_0 \cdot d}{\sqrt{(T_0)}} \cdot \frac{1}{\mu} \cdot \sqrt{\left[\frac{\gamma M}{R} \cdot \left(\frac{2}{1+\gamma}\right)^{(\gamma+1)/(\gamma-1)}\right]}.$$

This is therefore controlled by the inlet pressure, the gas properties and the jet diameter and so these tests

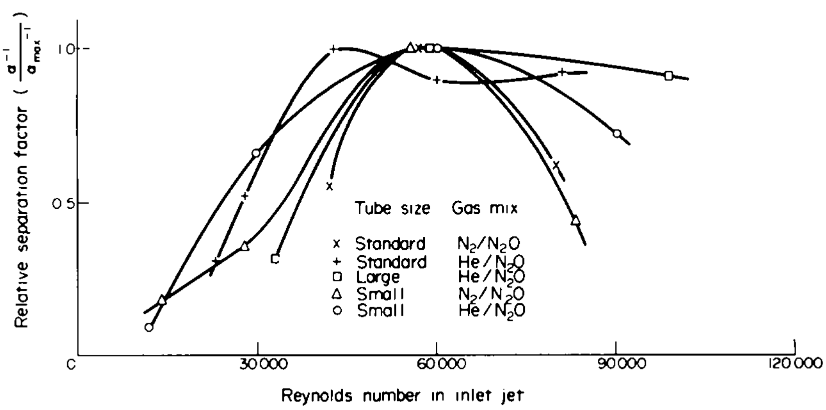


FIG. 4. Effect of inlet condition at 1 atm outlet.

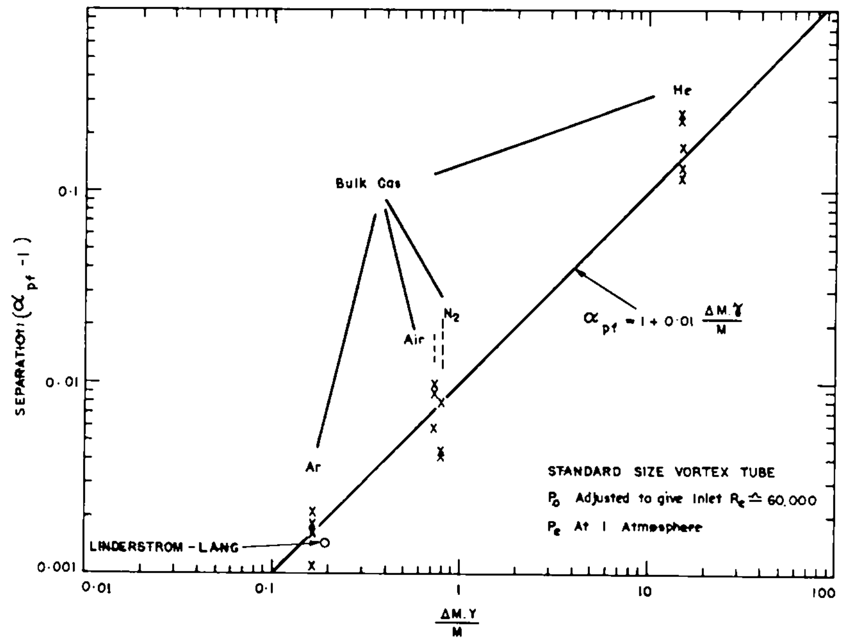


FIG. 5. Effect of centrifugation parameter.

effectively gave a range of *Re* in the inlet jet. Results from these tests are shown on Fig. 4 where the lines join points of differing inlet pressure operating on constant tube size and bulk gas. It can be seen that there is an optimum *Re* of about 60000 for maximum separation. For the helium bulk gas this *Re* occurred at inlet pressures of 4.5, 11.6 and 23 atm for the large, standard and small tubes respectively.

4. EFFECT OF GAS PARAMETERS

The steady state separation factor across the radius in a binary gas mixture rotating with constant angular velocity and having peripheral tangential velocity V is [3]:

$$\alpha = \exp\left(\frac{\Delta M \cdot V^2}{2RT}\right).$$

Taking this velocity in the present case with stationary walls to be the peak tangential velocity and to be proportional to the sonic velocity in the inlet jet, the separation factor becomes:

$$\alpha = \exp\left(A \cdot \frac{\Delta M \cdot \gamma}{M}\right) \simeq 1 + A \cdot \frac{\Delta M \cdot \gamma}{M}.$$

The flow pattern within a vortex tube is much more complex than this [2] but if the separation is by centrifugation and conditions such that the flow pattern is constant there should be a simple relationship between $(\alpha - 1)$ and

$$\left(\frac{\Delta M \cdot \gamma}{M}\right).$$

Experiments were made on the standard size tube using gas mixtures He/N_2O, N_2/N_2O, air/CO_2 and Ar/N_2O in which the parameter $\Delta M\gamma/M$ has values 15, 0.8, 0.73 and 0.165 respectively, a range of nearly two decades, with inlet pressure set to obtain the optimum *Re* and the peak separations were found. The results are plotted on Fig. 5 and show that the separation does appear to follow the assumed relationship. The value obtained by Linderstrom-Lang [1] is also given on the graph for comparison.

5. EFFECT OF OVERALL PRESSURE RATIO

The initial tests at 1 atm outlet condition had shown that the separation increased with increasing inlet pressure only until the optimum *Re* was obtained. It

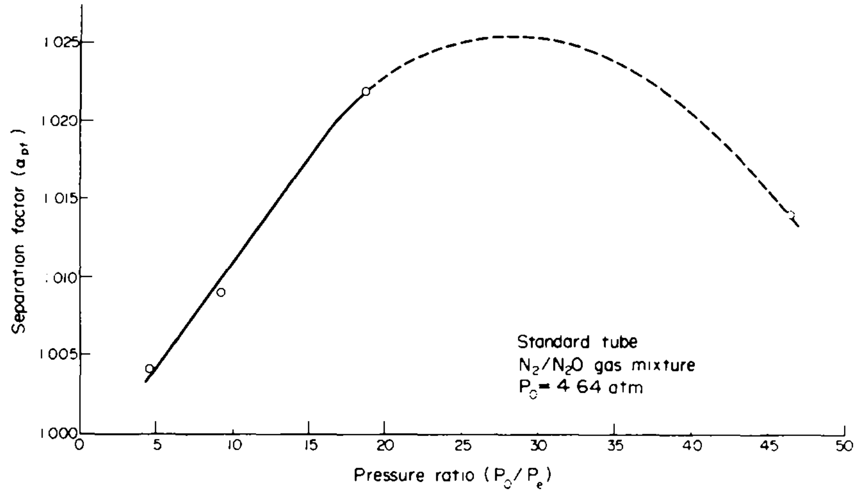


FIG. 6. Effect of outlet pressure.

was thought of interest to find the effect of reducing outlet pressure below atmospheric. This was difficult because the gas analyser only operated at atmospheric pressure and so gas was collected in large plastic bags held within low pressure enclosures. These bags were then compressed to provide sufficient gas at atmospheric pressure to operate the analyser.

Results from such tests with the standard size tube are shown on Fig. 6. Initially separation factor increased uniformly with pressure ratio but ultimately reduced again. Very few experiments were possible because of the difficulty in collecting the gases but these results encouraged the belief that the separation factor would be proportional to pressure ratio at least over some wide range. This pressure ratio includes the drop over the inlet and outlet orifices and also the drop across the vortex.

The results obtained in all the tests undertaken are shown on Fig. 7 with the separation plotted against a dimensionless group including the centrifugation parameter, the pressure ratio and the Schmidt number. This latter group was included on the general ground that diffusion rate must be a significant parameter in the separation process and trial plots showed that an improved relationship was obtained. Schmidt number was estimated by the method of Bird *et al.* [4] and varies over a range of 1.11 for Ar/CO_2 to 2 for He/N_2O. The figure includes all results with inlet conditions at or below the optimum *Re* and with pressure ratio in the range 4 to 35 for all size tubes and all gas mixtures. It will be seen that the standard size tube results generally lie within a band of about ±50% with this width determined more by scatter at each condition than by other variants. Results for the large

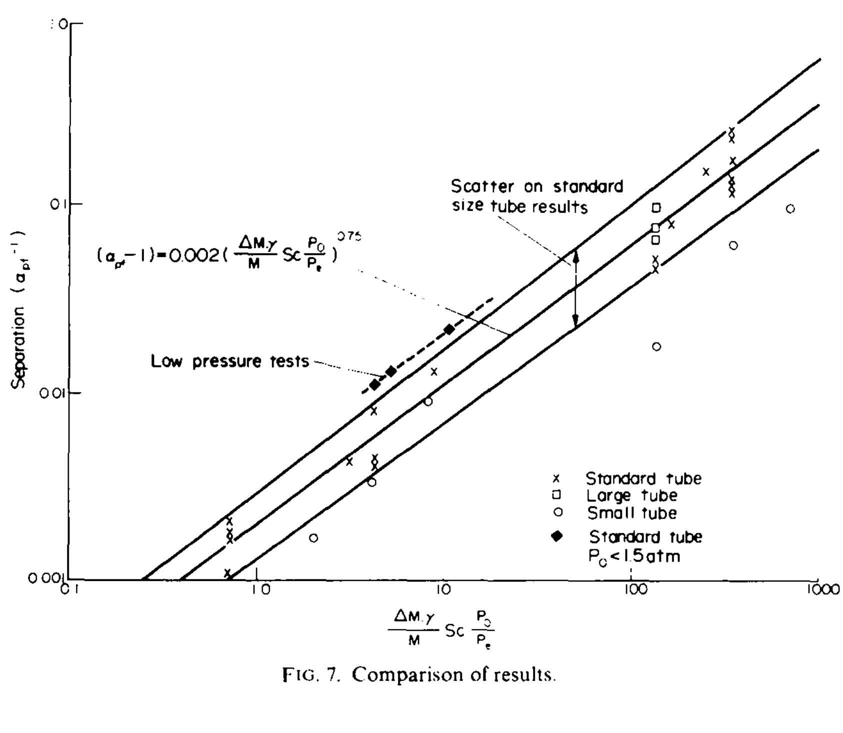


FIG. 7. Comparison of results.

tube also fit within this boundary but results for the small tube are consistently below the suggested correlation. Overall the results confirm the postulated parameter group terms.

6. EFFECT OF REDUCED INLET AND OUTLET PRESSURES

If with the outlet pressure substantially subatmospheric, say 0.25 atm, the inlet pressure is reduced the separation factor also reduces but apparently not as much as predicted by the suggested correlation. Points derived in this way are also shown on Fig. 7 as indicated with $P_0 < 1.5$ atm. They form a separate group lying above the scatter band about the correlation and therefore suggest that improved performance results from operating the vortex tube at low interior pressure. These are all tests with N_2/N_2O mixture. Inlet stagnation pressure P_0 varies from 1.41 to 0.58 atm and exit pressure P_e from 0.25 to 0.125 atm.

7. CONCLUSIONS

The results appear substantially to confirm the postulate that separation is primarily dependent upon centrifugation and also indicate in comparing the standard and large tubes that the performance is the same if the effect of overall pressure drop is considered. There is a falling off in separation factor above an inlet $Re \simeq 60000$ for all gases and tube sizes tested. There appears to be an increased separation factor at a given pressure drop where the inlet pressure is about 1 atm or lower.

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INFLUENCE DES CONDITIONS EXPERIMENTALES DES DIMENSIONS PHYSIQUES ET DES CARACTERISTIQUES DU FLUIDE SUR L'EFFICACITE DE LA SEPARATION DES GAZ DANS UN TUBE LINDERSTROM LANG A TOURBILLON

Résumé Linderstrom-Lang a montré qu'une séparation partielle des composants d'un mélange gazeux se produit lorsqu'il s'écoule dans un tube à tourbillon de type particulier. Le présent travail confirme cet effet. Ayant expérimenté plusieurs mélanges gazeux et plusieurs tubes de dimensions différentes, on a montré qu'il existe un nombre de Reynolds critique d'admission donnant une séparation maximale par ce procédé. Une relation empirique a été obtenue qui permet de prédire de façon satisfaisante les performances dans un domaine étendu des paramètres du gaz et des pressions appliquées.

EINFLUSS DER BETRIEBSBEDINGUNGEN, DER ABMESSUNGEN UND DER FLUIDEIGENSCHAFTEN AUF DIE GASTRENNLEISTUNG EINES LINDERSTRØM-LAND-WIRBELROHRES

Zusammenfassung — Linderstrøm-Lang berichtete, daß beim Durchströmen einer besonderen Wirbelrohr-Bauart eine partielle Trennung der Komponenten eines Gasgemisches auftritt. Die vorliegende Arbeit bestätigt diesen Effekt und zeigt anhand verschiedener Gasgemische und mehrerer verschiedener Rohrgrößen, daß eine kritische Einlauf-Reynolds Zahl existiert, bei der die Einrichtung eine maximale Trennwirkung aufweist. Es wird eine Korrelation abgeleitet, mit der in einem großen Bereich von Gasparametern und Drücken die Leistung befriedigend berechnet werden kann.

ВЛИЯНИЕ РАБОЧИХ УСЛОВИЙ, ФИЗИЧЕСКОГО РАЗМЕРА И ХАРАКТЕРИСТИК ЖИДКОСТИ НА РАЗДЕЛЕНИЕ ГАЗА В ВИХРЕВОЙ ТРУБКЕ ЛИНДЕСТРОМА-ЛОНГА

Аннотация — По данным Линдестрома-Лонга частичное разделение компонентов газовой смеси происходит при прохождении ее по вихревой трубке определенного типа. Настоящая работа подтверждает это и с помощью различных газовых смесей и разных размеров трубки показывает, что имеется критическое число Рейнольдса на входе для максимального разделения с помощью вихревой трубки. Получено соотношение, удовлетворительно описывающее коэффициент полезного действия в широком диапазоне изменения параметров газа и внешнего давления.