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Exploratory experiments on free expansion and interference of slit jets*

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RAREFIED gas free expansions from slots were surveyed using an impact pressure probe. Two general types of flow field were studied, the first from single slots and the second resulting from the interference of two intersecting slot expansions. Flows were of helium, argon and nitrogen gases at Reynolds numbers of ~ 1 to 2000 and pressure ratios of $\sim$ 1.3 to 100. Mass flow rates were measured and flow coefficients were computed. Transverse and axial impact pressure profiles are presented in the main body of the paper together with certain preliminary interpretations.

Swobodną ekspansję rozrzedzonego gazu od szczelin badano za pomocą czujników udarowego ciśnienia. Rozważono dwa typy pól przepływu — pierwszy z pojedynczym splotem, drugi powstały w wyniku interferencji dwóch przecinających się przepływów szczelinowych. Badano przepływy helu, argonu i azotu przy liczbach Reynoldsa od 1 do 2000 i stosunków ciśnienia od 1.3 do 100. Mierzono prędkości przepływu masy, a następnie obliczano współczynniki przepływu. Profile poprzecznego i osiowego ciśnienia udarowego przedstawiono w głównej części pracy, podając również niektóre wstępne interpretacje otrzymanych rezultatów.

Свободное расширение разреженного газа от щелей исследовано при помощи датчиков ударного давления. Рассмотрены два типа полей течения — первое с единичным предкрылком, второе возникшее в результате интерференции двух пересекающихся щелевых течений. Исследованы течения гелия, аргона и азота при числах Рейнольдса от 1 до 2000 и при отношениях давления от 1,3 до 100. Измерены скорости течения массы, а затем вычислены коэффициенты течения. Профили поперечного и осевого ударного давления представлены в главной части работы; приводим тоже некоторые предварительные интерпретации полученных результатов.

1. Introduction

CURRENT developments in applications of gas dynamic methods to isotope separation [1] have exposed gaps existing in our understanding of the fluid dynamics of planar jets issuing from slots. These gaps are particularly evident in a geometry of present interest in which two low Reynolds number slot jets are given intersecting directions of flow. The work described in this paper was initiated to help selecting adequate theoretical models of this complex flow and also to provide preliminary qualitative data aiding in the design of advanced experimental systems. A set of very simple experiments was performed using the Fluid Mechanics Laboratory low density wind tunnel at the University of California Berkeley Campus. In these experiments the impact pressure fields of intersecting and single free slot-jet expansion were surveyed using an impact pressure probe under various conditions of Reynolds number, pressure ratio and geometry. In addition, mass flow rates were measured and flow coefficients determined.

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2. Experimental set-up

A stagnation chamber fixed to a longidutinal traversing mechanism was mounted in the low pressure test section. The expansion gas was fed to the stagnation chamber from high pressure gas storage bottles, through standard pressure reduction valves and a fine needle valve. A Hastings Model ALL-5KP or, alternatively, a 50KP mass flow transducer, both with digital read-out, was connected to the input gas circuit to measure the rate of gas flow.

The stagnation chamber was connected to the pressure head of an MKS Baratron type 77 Electronic Pressure Meter (10 or 30 Torr range as required). Two types of stagnation chambers were employed. In the case of single jet experiments a 9″ dia., 4″ long cylinder (Fig. 1a) was used. For crossed jets experiments the stagnation chamber was compos-

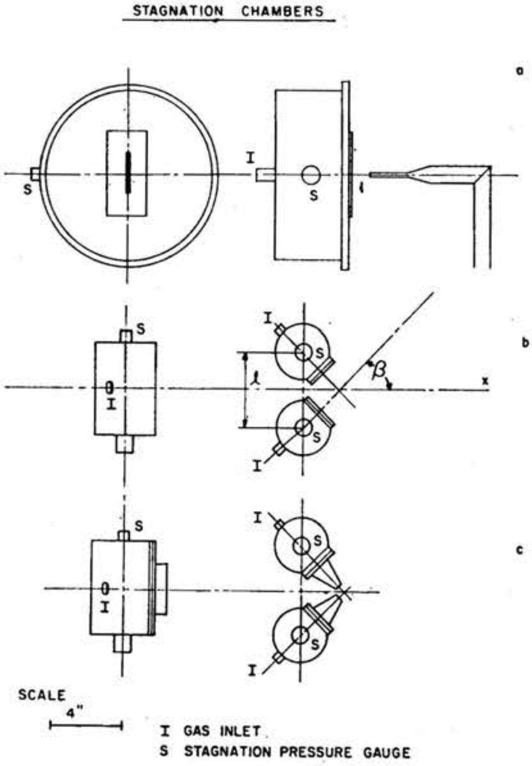


FIG. 1.

ed of two 3″ dia., 5″ high cylinders whose lateral distance l and angular position β (Fig. 1b, c) could be adjusted within wide limits. Both cylinders were connected to a single gas feed tube and a single stagnation pressure head. Thus individual adjustment of pressure or flow rate was precluded. The slits were cut in $2'' \times 5'' \times 1/8''$ brass plates or 0.004″ thick brass shimstock (Fig. 2a) and were fixed to the stagnation chamber with an "0" ring to secure air tightness. To obtain an intersection of the jets closer to the jet exit plates nozzles were used which had the shape of cut-off hollow wedges (Fig. 2b). The intersecting jet flow was measured using a cylindrical, open-ended impact pressure tube of 0.084" ID × 0.095" OD. At a later stage, for the subsonic experiments, the impact pressure tube was flattened at the end to a 0.039" by 0.120" oval shape to increase resolution. In the

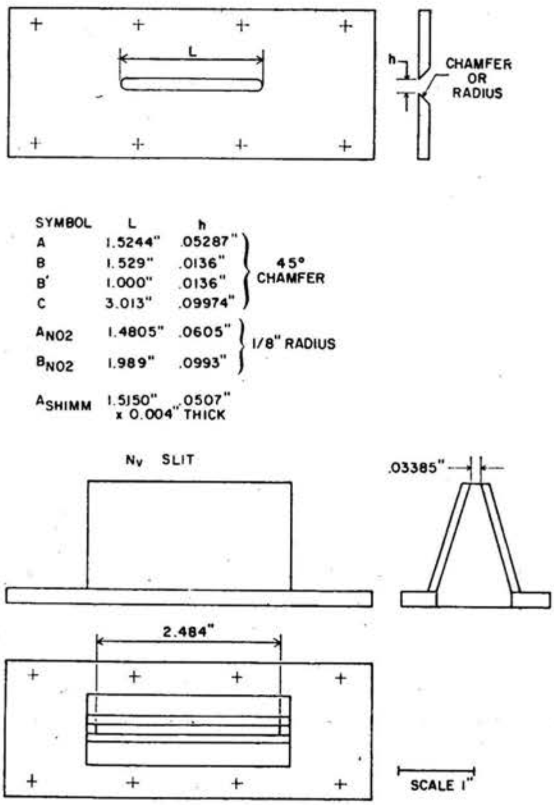


FIG. 2.

supersonic jet expansion measurements on single jets, both the 0.084 ID and a 0.176 ID × × 0.189 OD impact pressure tubes were used to allow further analysis of the impact pressure readings. The impact pressure tubes were fixed to a lateral traversing mechanism allowing for impact pressure distribution measurements. The impact pressure probe was connected to an MKS Baratron Type 77 pressure head and Electronic Pressure Meter (1 or 10 Torr range as required).

3. Crossed jet experiments

This set of experiments was carried out at subsonic jet velocities, with a few exceptions, as this was the most interesting range in view of future applications. The difficulties connected with interpreting crossed supersonic jet measurements which involve complicated three-dimensional shock boundaries were thus avoided.

The Reynolds number of jet flows in these studies was limited to a value of about 30. Below this value those oscillations disappeared which were observable as fluctuations in the pressure meter at higher Reynolds numbers and which could be attributed to jet instabilities. The Reynolds number (Re) for the subsonic range was based on the average flow velocity through the slit deduced from the Hastings Flowmeter readings, stagnation chamber pressure and room temperature.

The flattened impact pressure tube was placed parallel to the geometric axis of the system which gave a space resolution of about half the slit width. This probe was used to

Table 1. Parameters of crossed jet experiments.

Stagnation Chamber										
Slit	$\beta°$	Dist. c cylinders	Gas	p_{stg} Torr	p_{∞}	p_{stg}	M.F. SCCM	Re	Kn_{∞}	Fig.
$2\times B$	45	4.5	Ar	1.030	.6015	1.712	2531.1	30.80	0.35	3
$2\times B$	45	4.5	Ar	.3240	.1898	1.707	614.9	7.48	.11	4
$2\times B$	45	4.5	Ar	.1491	.08412	1.772	207.35	2.52	.25	5
$2\times B$	45	4.5	He	.3436	.1996	1.720	1415.7	1.97	.29	6
$2\times B$	45	4.5	He	.1726	.09916	1.740	543.4	.76	.56	7
$2\times B$	45	4.5	He	.1123	.06156	1.824	321.75	.45	.95	8
$2\times N$	30	6.75	Ar	.6040	.3517	1.717	1680.25	16.20	.059	9
$2\times N$	30	6.75	Ar	.3038	.1678	1.810	629.2	6.07	.124	10
$2\times N$	45	5.5	Ar	.6050	.3368	1.796	1716.0	16.54	.062	11
$2\times N$	45	5.5	Ar	.3040	.1719	1.768	679.25	6.55	.121	12
$2\times N$	60	3.9	Ar	.6126	.3402	1.801	1701.7	16.41	0.61	13
$2\times N$	60	3.9	Ar	.3200	.1778	1.800	717.15	6.91	.117	14
$2\times N$	60	3.9	Ar	.1788	.1007	1.776	307.45	2.96	.207	15

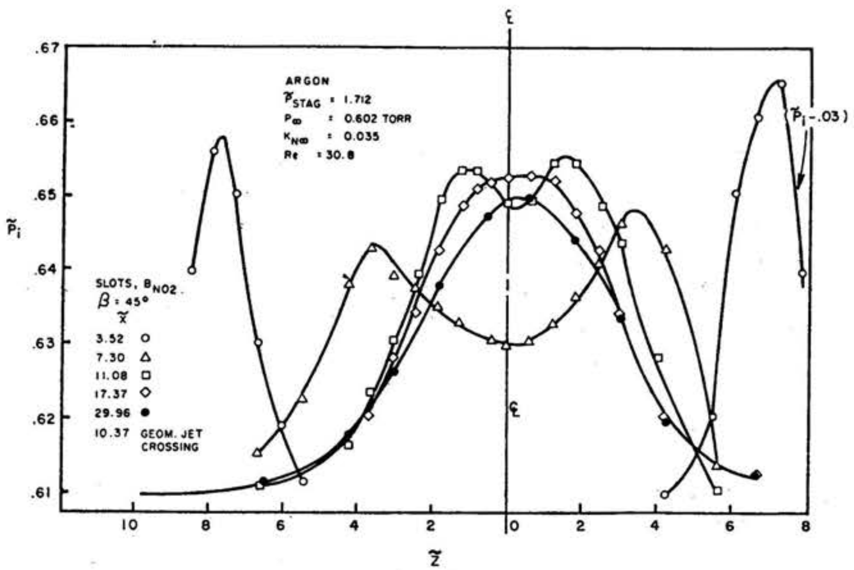


FIG. 3.

measure the lateral distribution of impact pressures in the plane of symmetry at mid slit height where, as shown by experiments on jets from single slits, the flow can be considered as two-dimensional. The distribution p_i was measured at different distances from the jet exit plane x for different lateral positions z. The pressures given in the results are non-di-

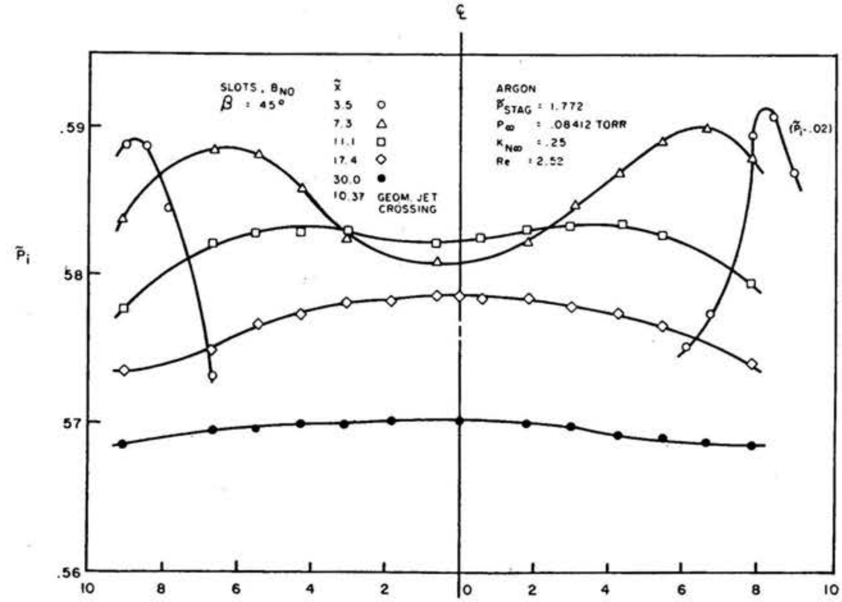


FIG. 4.

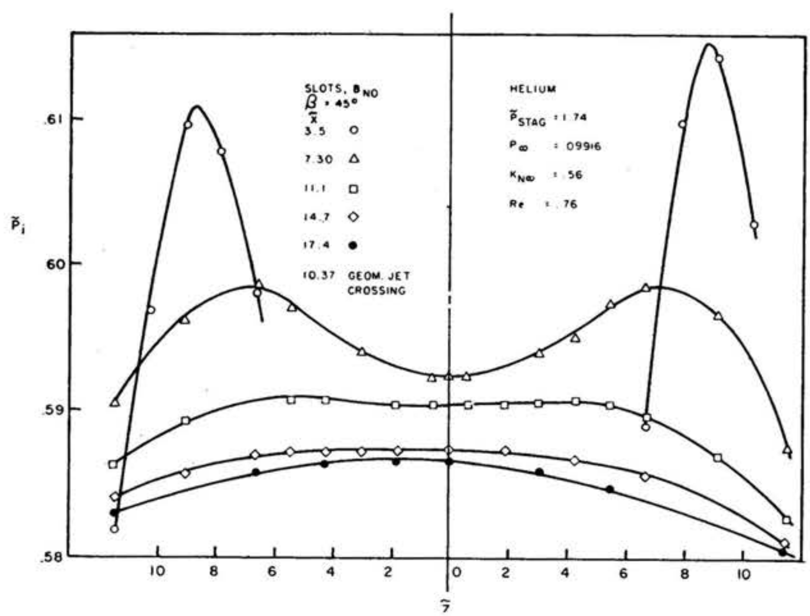


FIG. 5.

mensionalized by the stagnation pressure $\left(\tilde{p}_i = \frac{p_i}{p_{stg}}\right)$ and the distances by the slit width *h*. $\left(\tilde{x} = \frac{x}{h}, \tilde{z} = \frac{z}{h}\right)$. The expansion ratio is denoted by $\tilde{p}_{stg} = \frac{p_{stg}}{p_\infty}$.

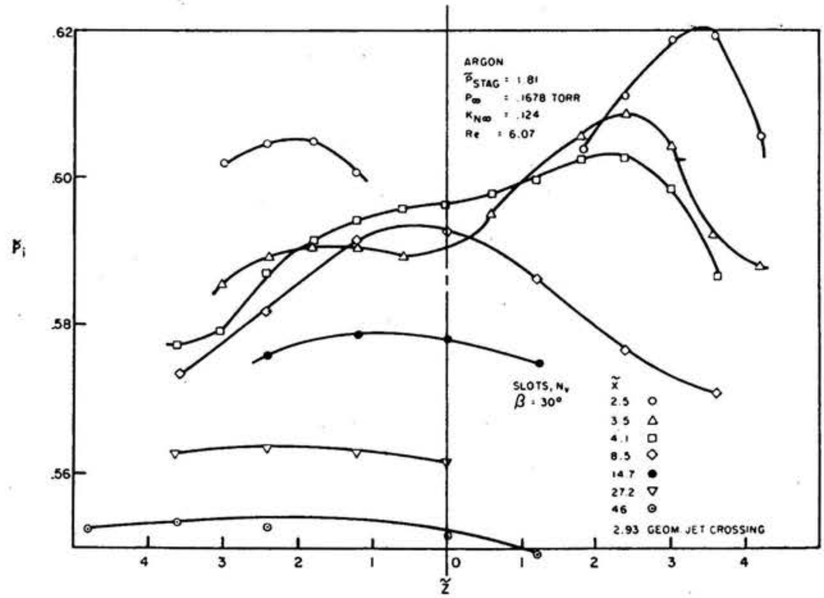


FIG. 6.

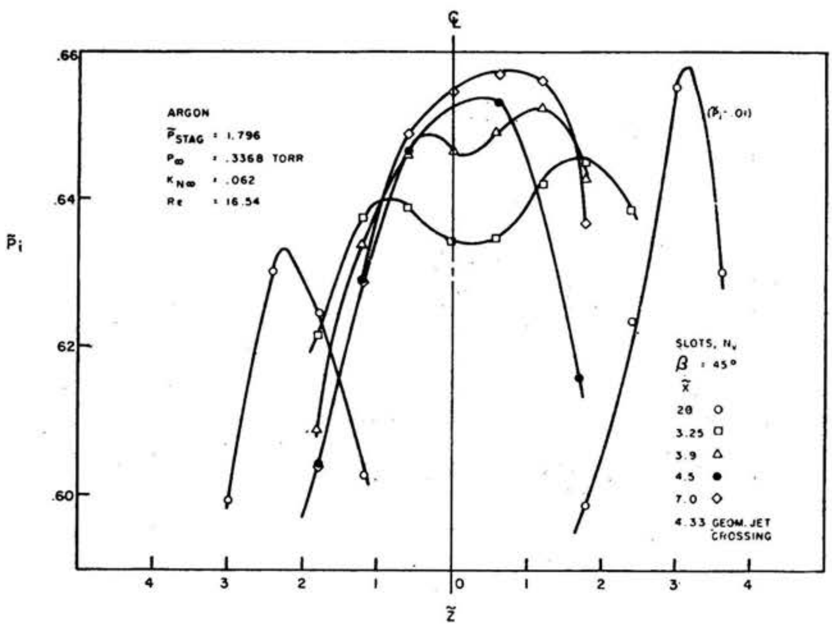


FIG. 7.

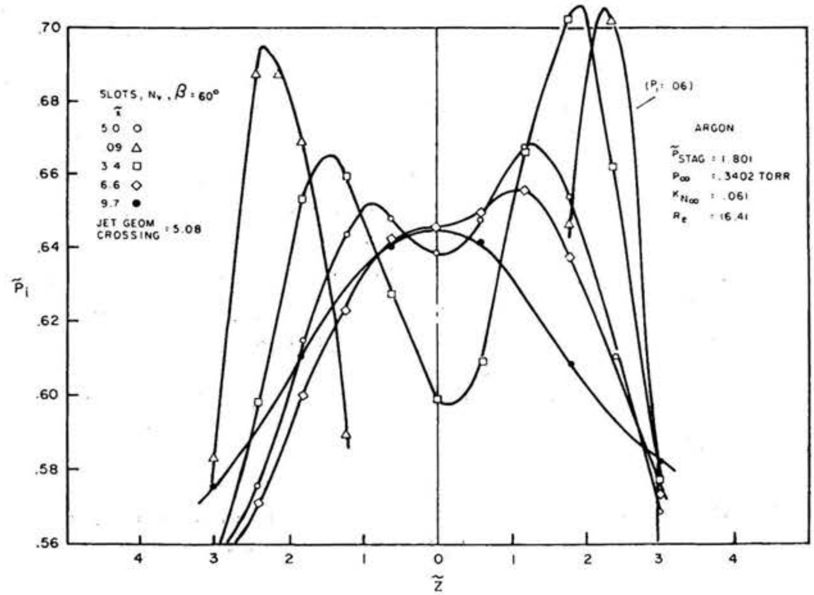

SLOTS, Nv, β = 60°
x̃
5.0 ○
.09 △
3.4 □
6.6 ◇
9.7 ●
JET GEOM CROSSING = 5.08
ARGON
P̃STAG = 1.801
P∞ = .3402 TORR
KN∞ = .061
Re = 16.41
P̃i
Z̃

FIG. 8.

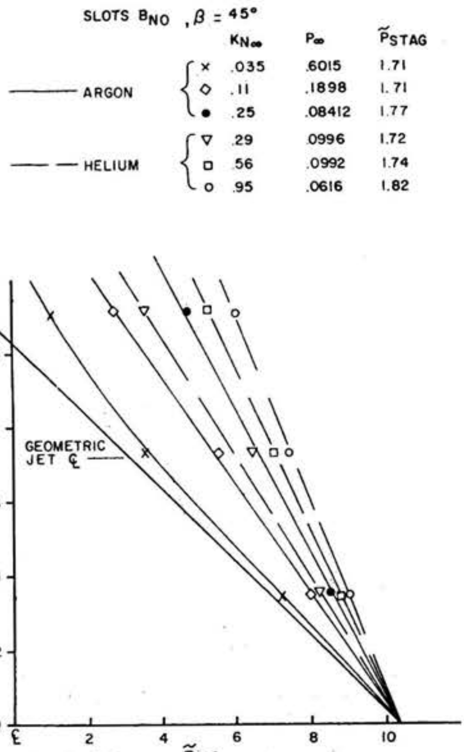

SLOTS BNO , β = 45°
KN∞ P∞ P̃STAG
ARGON
× .035 .6015 1.71
◇ .11 .1898 1.71
● .25 .08412 1.77
HELIUM
▽ .29 .0996 1.72
□ .56 .0992 1.74
○ .95 .0616 1.82
GEOMETRIC JET ℄
x̃
Z̃pp

FIG. 9.

Flow and geometric parameters of the crossed jet experiments are summarized in Table 1, and the results are shown in Figs. 3—8. Three geometric jet intersection angles were selected: sharp, $2\beta = 2\times 30°$; rectangular, $2\beta = 2\times 45°$; and flat, $2\beta = 2\times 60°$. The geometric jet crossing point was selected for two cases, the first being a near field intersection of about 5 slit widths from the slit exit plane (the distances and inclinations of the cylinders were adjusted accordingly). See Fig. 1c for stagnation chamber and Fig. 2b for the slits used. For the second case a far field intersection of about 15 slit widths was selected (Fig. 1b stagnation chamber, slit B_{NO2}, Fig. 2a). In this latter case, measurements were taken for $2\beta = 90°$ only. It was expected that at the slit widths distance no nozzle shape effects would be present. The gas used was primarily argon; however, to extend the Knudsen number helium was used for some far field jet intersection measurements. The Knudsen number $\mathrm{Kn}_\infty = \frac{\lambda_\infty}{h}$ is based on the slit width, h, and on the mean free path, λ_∞, at T_∞ room (chamber) temperature.

Before intersection the jet stream lines are inclined at a large angle relative to the impact pressure probe axis; hence the indicated pressures can only be of qualitative usefulness. Downstream, close to the crossing the streamline inclination is much smaller and the pressure readings become meaningful. From Figs. 3—8 it can be seen that the flow is appreciably and often strongly asymmetric in spite of the fairly symmetric stagnation chamber and inlet gas tubing. To obtain a symmetric flow it may be necessary to impose very strict geometric requirements and to have separately controlled inlet gas feeds and individual stagnation pressure measuring equipments.

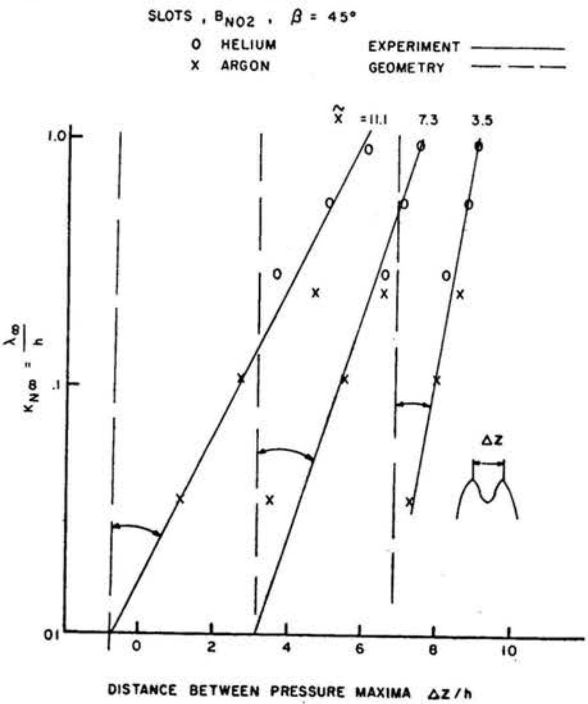


FIG. 10.

The pressure distribution curves indicate a rather strong spreading trend as the pressure at infinity is reduced or Kn_∞ is incresaed. We may take half the distance between impact pressure peaks, Δz as being the distance between the jet intersection center line and a single

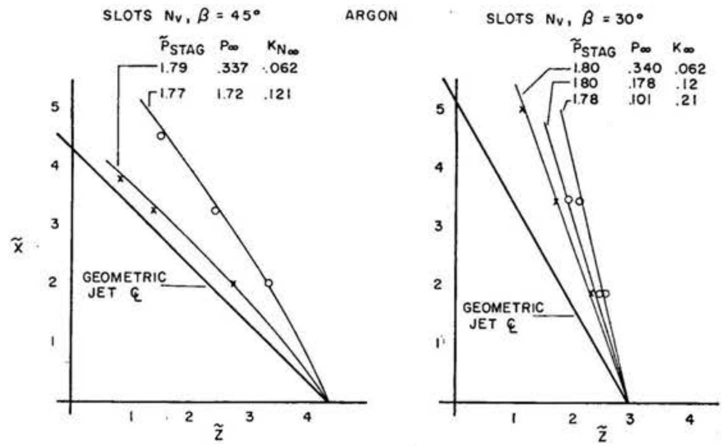


FIG. 11.

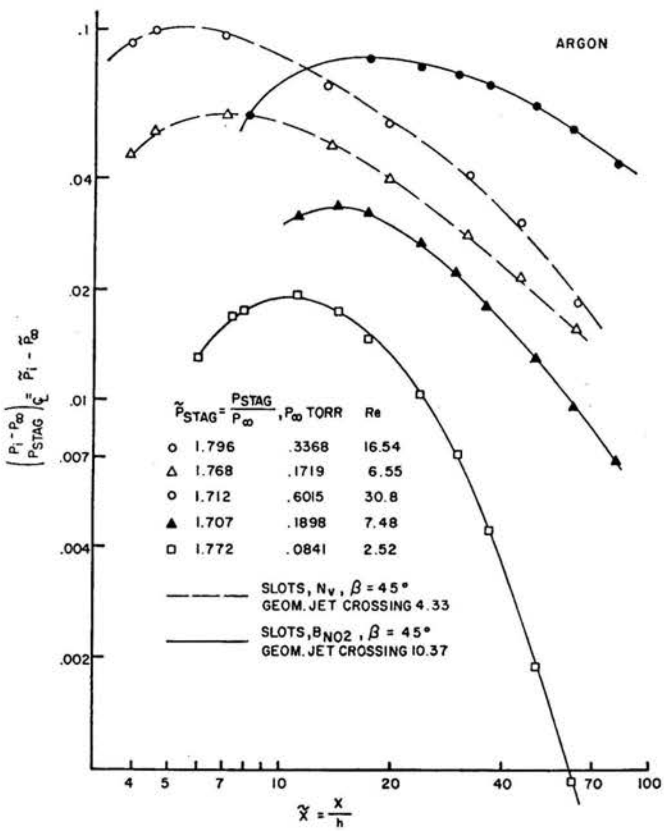


FIG. 12.

pressure peak. This normalized distance, $\tilde{z}_{pp}(\tilde{x})$, $\left(\tilde{z}_{pp}(\tilde{x}) = \frac{z_{pp}(\tilde{x})}{h}\right)$ is plotted in Fig. 9 as a function of $\tilde{x}$ for argon and helium at various values of p_∞. It can be seen that for $p_\infty \leqslant$ $\leqslant 0.2$ Torr the peak position varies linearly with the distance from the jet exit. This behavior seems to indicate that the jet curvature is highest close to the point of intersection. In Fig. 10, in which the relative peak separation $\Delta z/h$ is correlated with Kn_∞, we see the peak separation increasing as Kn_∞ increases. The variations of the non-dimensional pressure difference $\tilde{p}_i - \tilde{p}_\infty$ along the crossed jet axis for the close and far jet intersection indicate that the maximum pressure occurs beyond the geometric intersection point in agreement with the jet spreading noted above. The difference between the maximum pressure and the pressure at the geometric intersection point is only slightly larger in the near than in the far field intersection. There is not much to be drawn from a comparison of the axial ($\underset{\sim}{c}$) impact pressure distribution in the crossed jet case, Fig. 12, with that for the single

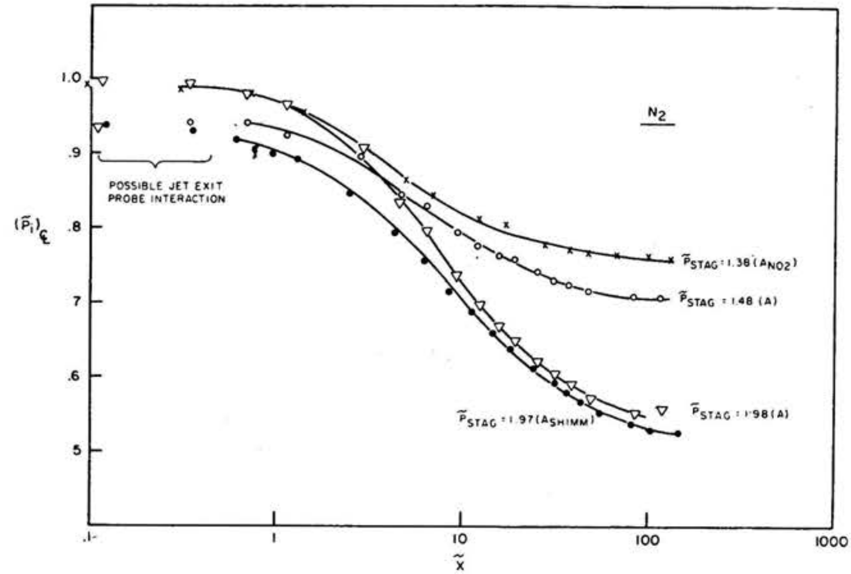


Fig. 13.

jet, Fig. 13, since the two cases are fundamentally dissimilar. It may be noted, however, that $\tilde{p}_i - \tilde{p}_\tau$ is always lower for the intersecting jet and falls off more rapidly with $-\tilde{x}$ once the maximum is passed.

4. Supersonic slit jet expansion

Measurements were obtained for the variation of the impact pressure along the geometric jet axis up to distance of about 130 slit widths using probes of 0.084" ID and of 0.176" ID. The main aim of these measurements was to develop data on the structure of a shock wave in an expanding jet, on the Mach shock wave, and on its dependence on the main flow parameters. It is expected that measurements with different hot wire probes would be useful in the quantitative evaluation of the measurements when fuller theoretical results of the expansion of jets become available. On the other hand, the most promising experimental methods for detailed information remain the methods of Doppler shift and Doppler broadening in electron beam fluorescence. These will be undertaken in the Berkeley

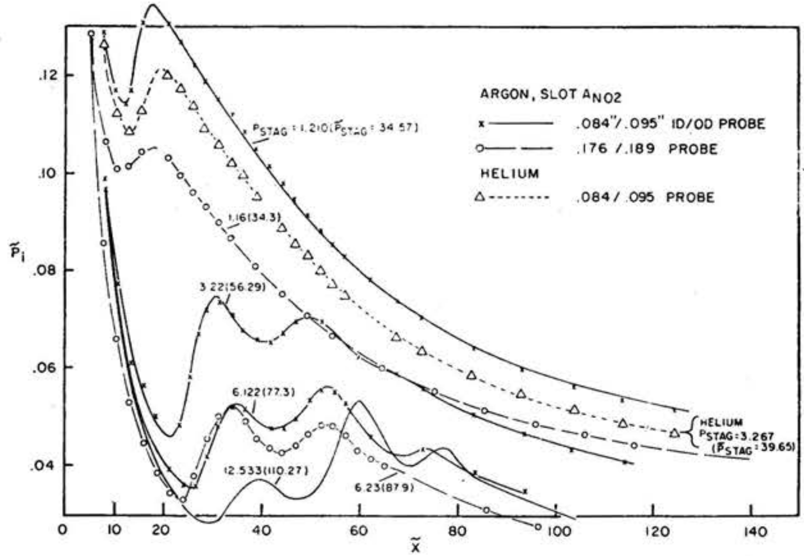


FIG. 14.

laboratory in the near future. The principal results are given in Figs. 14 and 15. It can be seen in these figures that at the lower stagnation pressures and expansion ratios a single shock wave structure exists. At higher stagnation pressures and expansion ratios other

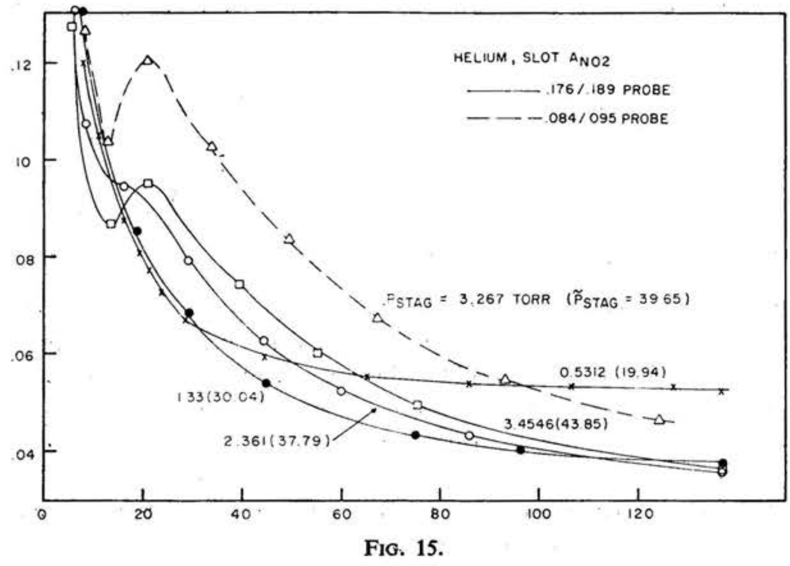


FIG. 15.

irregularities appear which may be caused by reflections of waves and other secondary features of what must be recognized to be a complicated shock-wave system. At lower stagnation pressures, in this case for He (Fig. 15), the shock-wave is too weak to be de-

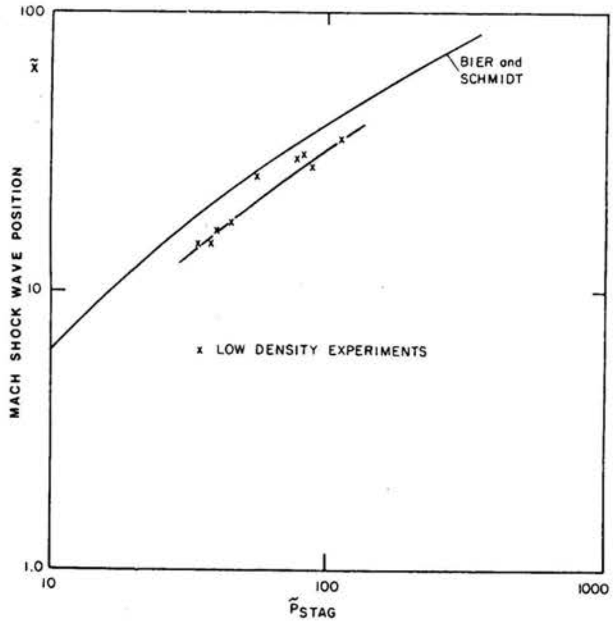
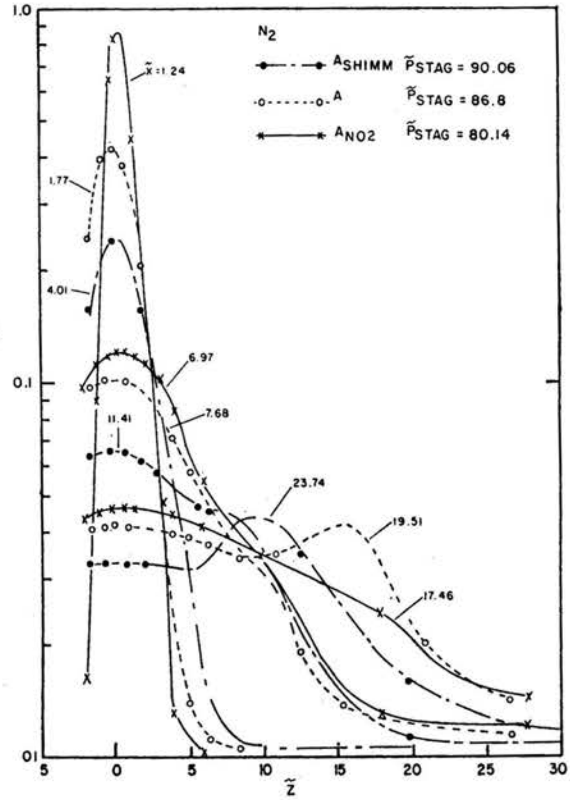


FIG. 16.

tectable. At an intermediate pressure, $p_{stg} = 3.455$, there remains only a change of slope (without change of sign) in the $\tilde{p}_i(\tilde{x})$ curve. The impact pressures, measured with the two different size probes, show a qualitative similarity, however, quantitatively the differences of the impact pressure values indicated are as high as 25%. Here a deeper insight into the meaning of pressure probe indications is necessary.

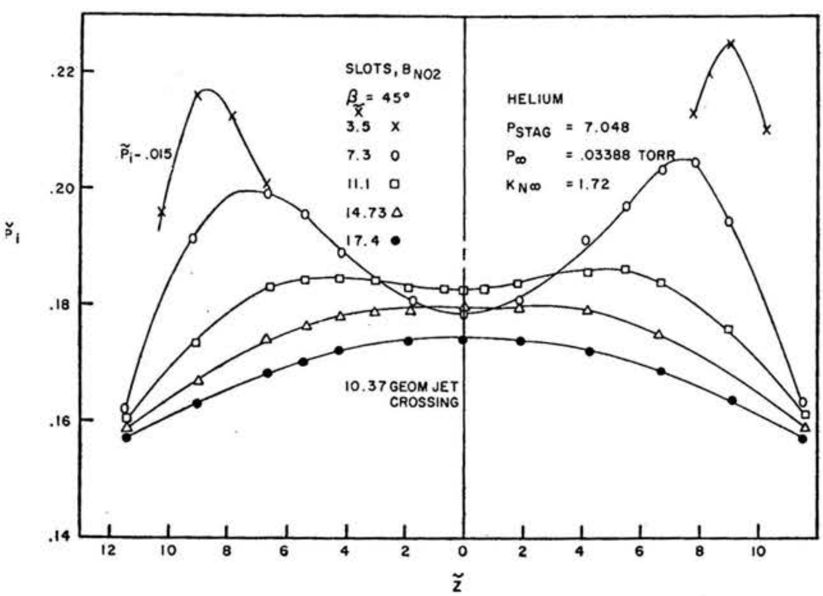
The variation of the Mach disk, shock-wave position, defined as the distance from the slit exit to the point of maximum positive pressure slope, is compared in Fig. 16 with the results of BIER and SCHMIDT [2] obtained from optical observations on high pressure slot jets. The experimental points which we have obtained lie at low pressures below the curve of Bier-Schmidt but indicate a similar variation with the expansion ratio $\frac{p_{stg}}{p_\infty} = \tilde{p}_{stg}$. Typical transverse impact pressure distributions are shown in Fig. 17. The expected larger spread of the jet as compared with the subsonic case is noticeable and the pressure bumps due to the barrel shocks are clearly visible. The measurements of Fig. 18 were taken using different slit cross-sections to see how they affect the pressure distribution. They indicate that at distances above about one slot width the effects of differences in the slit cross-section geometry is very small.

Measurements of longitudinal and transverse pressure distributions were taken for supersonic intersecting beams at the expansion ratio of $\tilde{p}_{stg} = 7.048$ and an angle of in-



N2
ASHIMM P̃STAG = 90.06
A P̃STAG = 86.8
ANO2 P̃STAG = 80.14
x̃ = 1.24
1.77
4.01
6.97
7.68
11.41
23.74
19.51
17.46
P̃i
z̃

FIG. 17.



SLOTS, BNO2
β = 45°
x̃
3.5 X
7.3 O
11.1 □
14.73 △
17.4 ●
HELIUM
PSTAG = 7.048
P∞ = .03388 TORR
KN∞ = 1.72
P̃i - .015
10.37 GEOM JET
CROSSING
P̃i
z̃

FIG. 18.

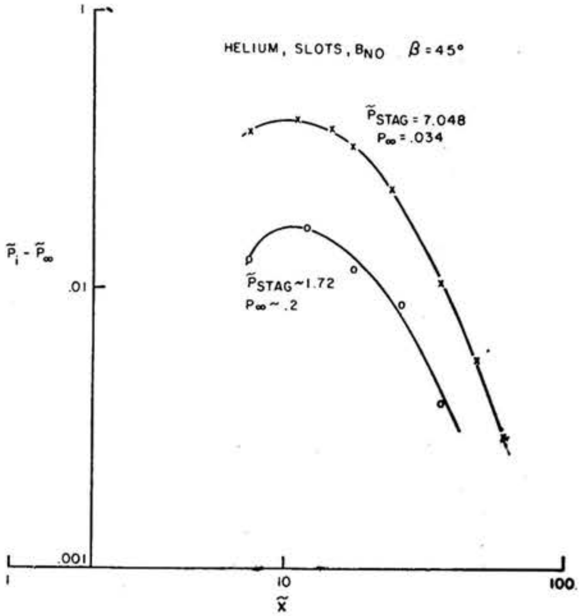


FIG. 19.

tersection of 90°. The longitudinal pressure distributions for an expansion ratio of 1.72 are also shown in Fig. 19 for comparison. The lateral pressure distributions are shown in Fig. 18 and can be compared with those of Fig. 5 corresponding to lower expansion ratios of about 1.8. All pressure distributions are qualitatively very similar, a result which requires more detailed velocity field measurements for its full explanation.

5. Miscellaneous

a. To check the validity of the assumption that the jet is two-dimensional in the near field, measurements of the variation of impact pressures along directions parallel to the long edge of the slit were taken for a typical subsonic and supersonic jet-pressure ratios. The pressure at $\tilde{p}_{stg} = 1.79$ is shown in Fig. 20 for three distances downstream of the exit. It can be seen that the $\tilde{p}_i$ variation is within 0.5% for regions varying between 80% of the slit length close to the exit to about 45% of the slit length at cross-sections about 70 slit width downstream. The supersonic jet expansion, represented in Fig. 21, shows a similar or even perhaps, more uniform distribution.

b. Discharge coefficients were measured for the geometrically similar set of nozzles A, B', C, making use of the existing experimental set-up. These have been correlated, Fig. 22, in terms of the coefficient $K' = K/a_t$ as a function of the Reynolds number based on the slit width and sonic conditions. In the above, K is the flow in SCCM and a_t is the sound speed. The correlation here for argon, helium and nitrogen shows a comparatively small scatter.

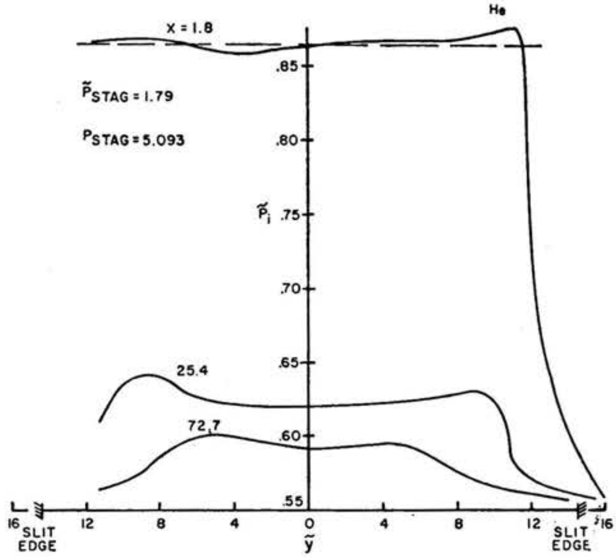

He
X = 1.8
$\tilde{P}_{STAG}$ = 1.79
P_{STAG} = 5.093
$\tilde{P}_i$
.85
.80
.75
.70
.65
.60
.55
25.4
72.7
16
12
8
4
0
4
8
12
16
SLIT EDGE
SLIT EDGE
$\tilde{y}$

FIG. 20.

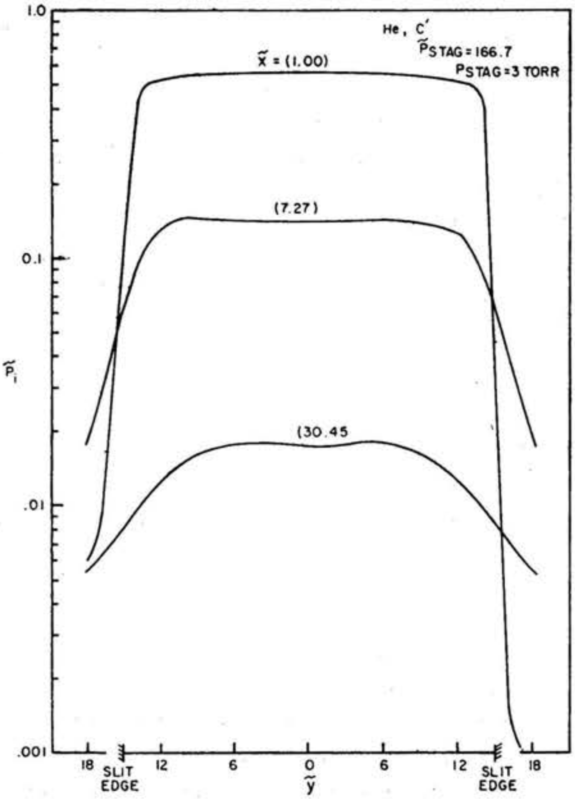

He, C'
$\tilde{P}_{STAG}$ = 166.7
P_{STAG} = 3 TORR
$\tilde{x}$ = (1.00)
(7.27)
(30.45
1.0
0.1
.01
.001
$\tilde{P}_i$
18
12
6
0
6
12
18
SLIT EDGE
SLIT EDGE
$\tilde{y}$

FIG. 21.

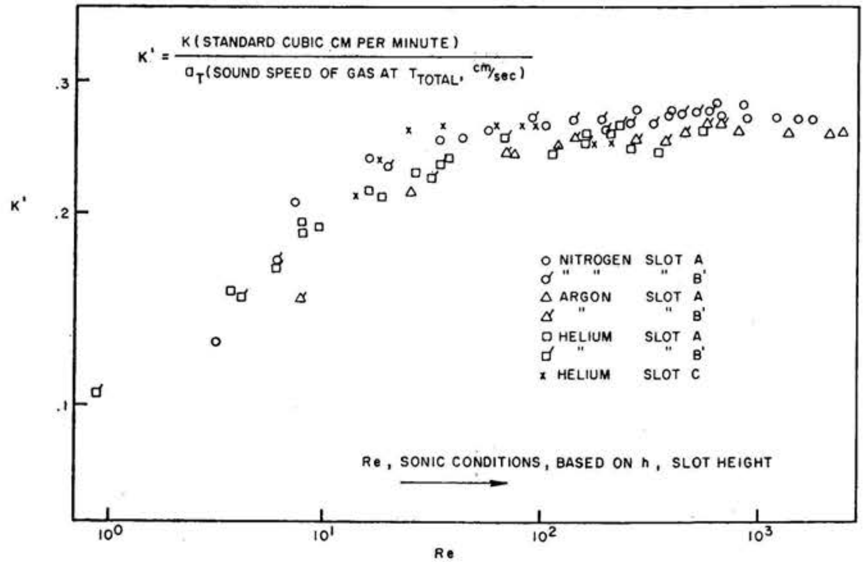


FIG. 22.

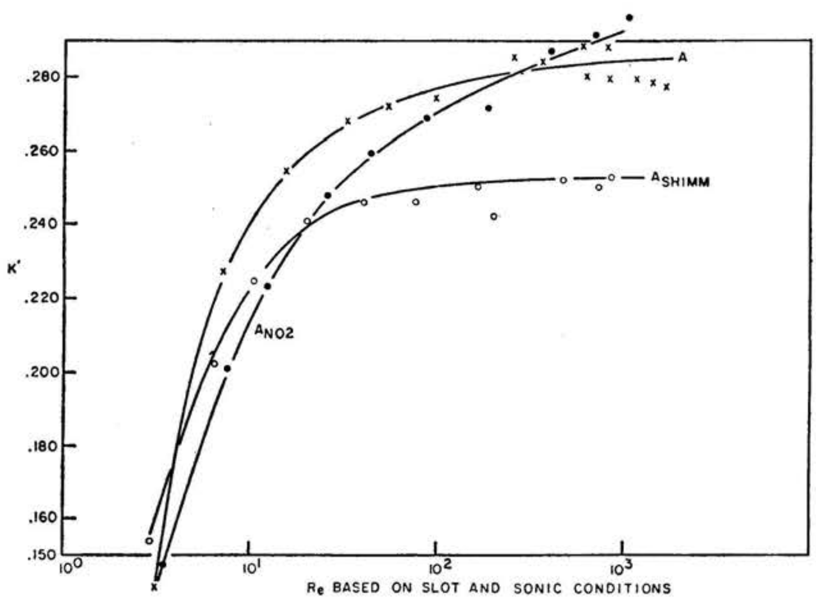


FIG. 23.

The correlation for nitrogen flows from a 0.051″ slot cut in shim stock of 0.004″ thickness (A_{Shim}) is shown in Fig. 23 and compared with flows from the A and A_{NO2} slots. The shim cross-sections is radically different from the more gently shaped slot cross-sections of A or A_{NO2}. We see here a significant difference in behavior particularly for Re > 50, above which K' for the shim reaches asymptotic values which are lower than for the other nozzles.

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