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SECOND QUARTERLY PROGRESS REPORT ON

NSR 22-009-288

7-1-68 thru 9-30-68

A Study of Fluid Dynamics of Gaseous Nuclear Rockets

A comprehensive review of the state of knowledge of vortex flows and how such flows may or may not be used for fluid dynamic containment of a gaseous nuclear fuel has been continued. Work this past quarter has concentrated on empirical correlations of experimental data available in the literature. This work has been reported in Ref. (1) and only the principal results obtained in it will be summarized herein.

Vortex experiments run at high Reynolds numbers typically have some turbulence associated with them. This introduces an uncertainty into the flow that cannot be removed by completely theoretical means without some advances in the present knowledge of the basic phenomena of turbulence. It is therefore currently necessary to rely on some empirical information in any attempt to predict vortex flow patterns with high Reynolds numbers.

One method of approach is to compare a laminar flow theory which includes as many important features of the flow as possible with experimentally obtained velocity profiles. The differences between theory and experiment are then used to infer a difference between the effective turbulent eddy viscosity and the laminar viscosity. The laminar flow theory chosen in Ref. (1) for use in this comparison is that by Rosenzweig, Lewellen and Ross(2). Figure (1) shows a comparison of the results of this theory with an experimental velocity profile obtained by Travers(3) under what he believed to be laminar flow conditions. The agreement, although not perfect, appears to be quite satisfactory. It is concluded that the theory is adequate to predict a completely laminar flow and thus it is reasonable to attribute differences between theory and experiment to turbulence in the case of high Reynolds number experiments.

The ratio of effective eddy viscosity μ^* to actual laminar viscosity μ, which was deduced in the manner described in the preceding paragraph is plotted in Fig. (2) for data available in the bibliography given in Ref. (4). The data appear to correlate reasonably well when plotted against the parameter $Re_t\left(\frac{u}{v}\right)^{1/2}(D/L)^{0.28}$ where Re_t is the Reynolds number based on tangential velocity and the radius at the outside of the vortex; u/v is the ratio of radial to tangential velocity at the outer radius of the vortex; and D/L is the diameter-to-length ratio of the vortex chamber. The exponents in this parameter were chosen to obtain the best possible least squares fit to all the data. The key to the data points is given in the Table in Appendix A. This table also includes information on other experiments not included on Fig. (2) due to a lack of sufficient information.

Figure (2), perhaps, over-emphasizes the role of turbulence in determining the velocity distribution in a vortex. In some cases large values of μ^*/μ result from rather small differences between laminar theory and experiment. Figure (3) shows a plot of the circulation at the edge of the exhaust radius as a function of a boundary-layer interaction parameter. The solid line is the theoretical curve obtained as the radial Reynolds number based on radial mass flow becomes very large. The dashed line is fared in to fit the data. The difference between the two lines is assumed to be caused by turbulence, although part of this difference could actually be caused by approximations used in the boundary-layer theory used to generate the solid line. The direct use of Fig. (3) probably provides as good an estimate of Γ_e/Γ_o for any experiment as does the more elaborate procedure of estimating μ^* from Fig. (2) and using this in the laminar theory of Ref. (2).

The empirical correlations of the past quarter have been aimed at providing the information required to predict the flow pattern in any given vortex tube. This effort will be continued, since the degree to which one can do this forms an essential part of a comprehensive review of the state of knowledge of vortex flows.

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Project Supervisor

September 30, 1968

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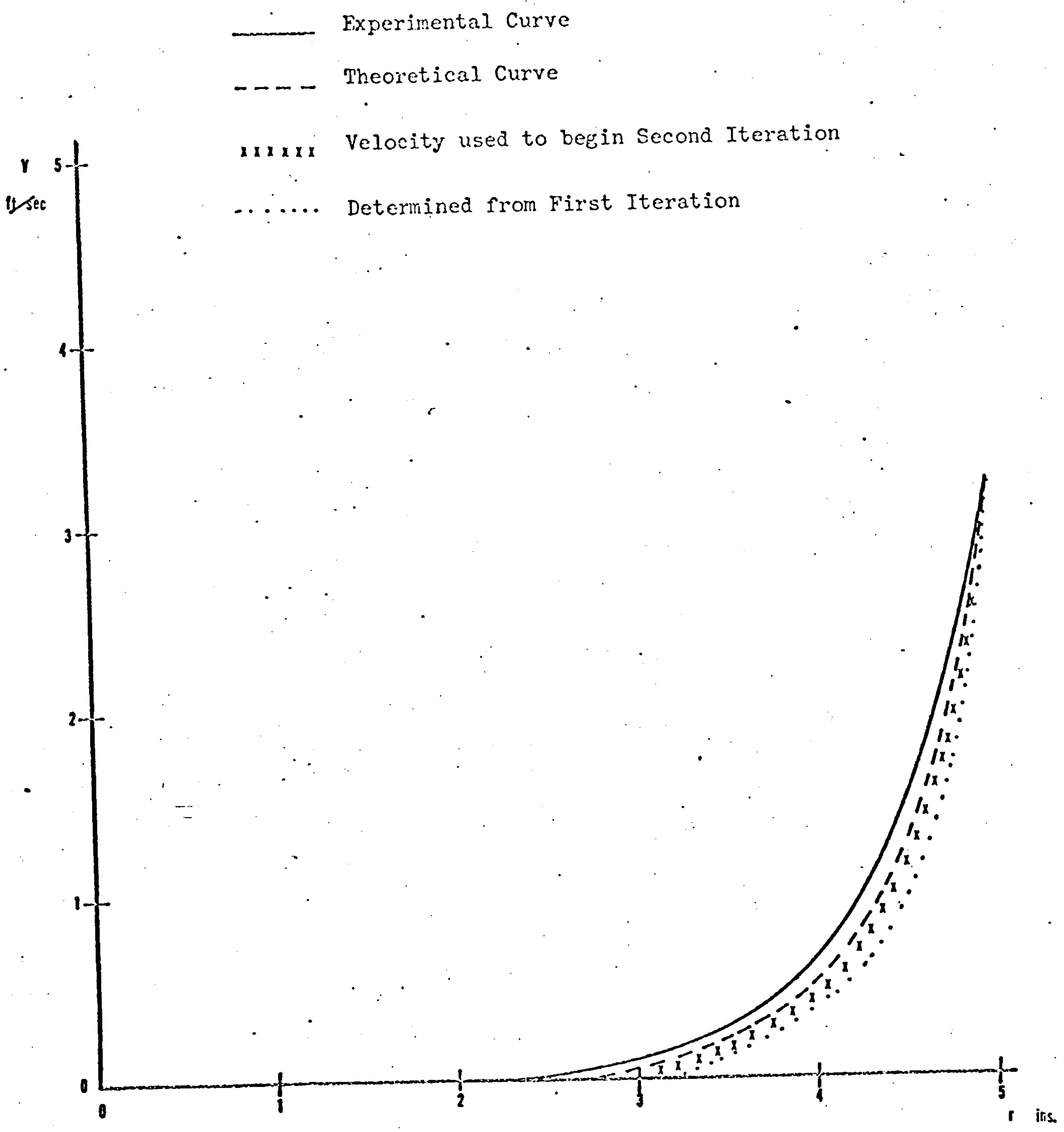


Figure 1. Tangential Velocity Profile Showing Experimental Curve and Theoretical Curve Based on Boundary-Layer Interaction Theory.

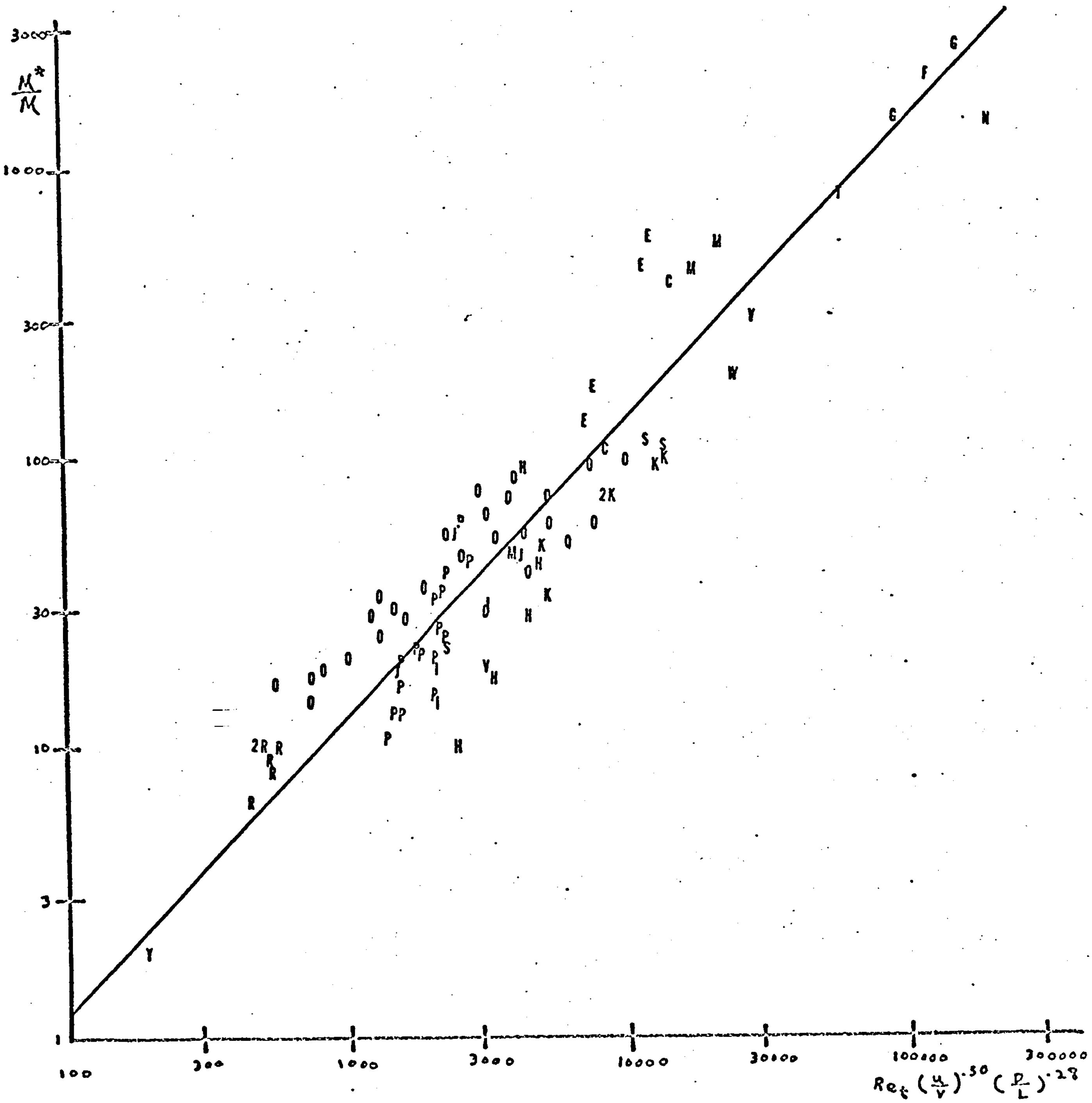
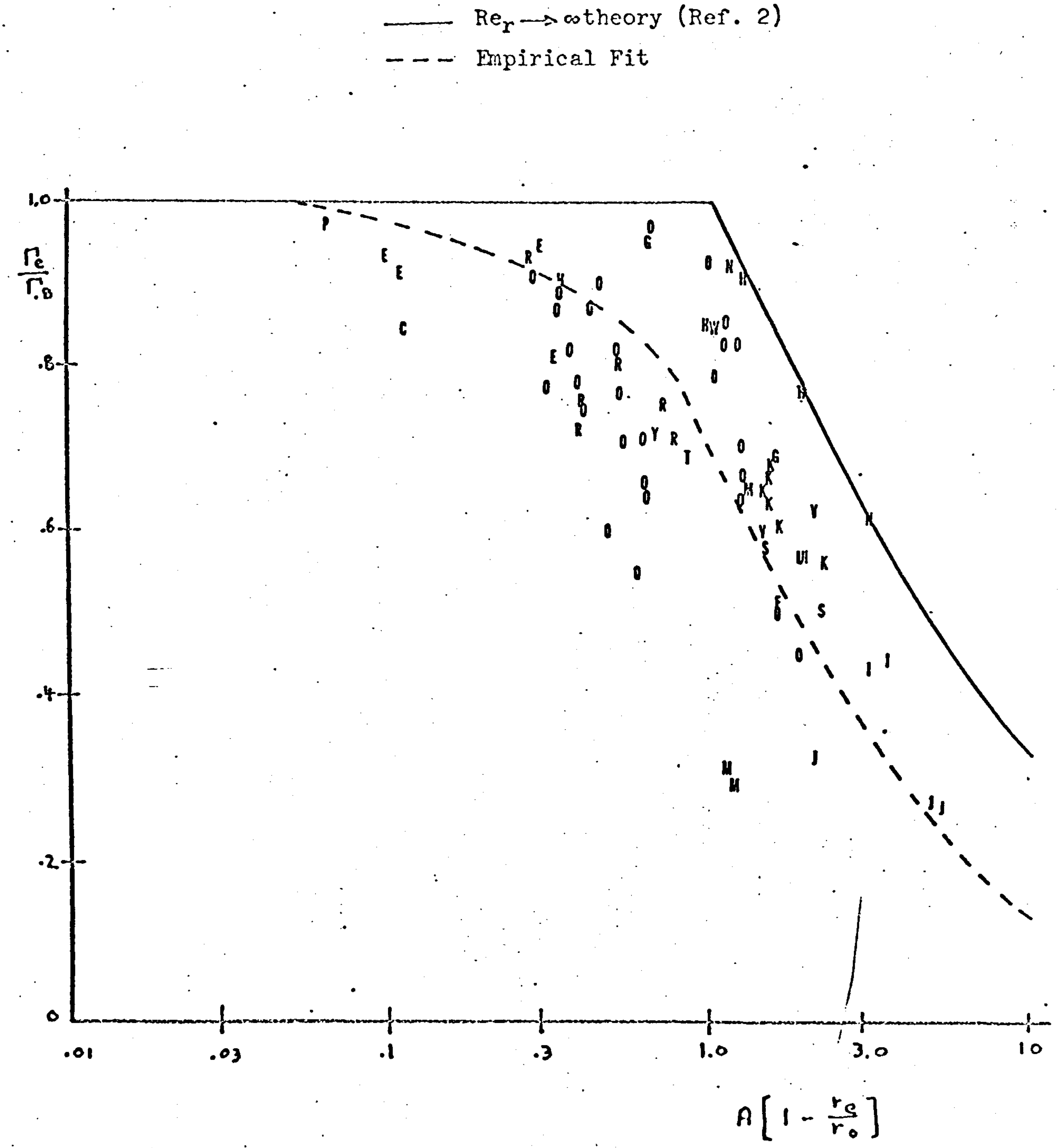


Figure 2.The Variation of the Ratio of Laminar Radial Reynolds to Effective Turbulent Radial Reynolds Number with $Re_t(\frac{u}{v})^{.50}(\frac{D}{L})^{.28}$

Figure 3. The Variation of the Ratio of the Circulation at the Exit to the Circulation at $\frac{r}{r_o} = .8$ with $A\left[1 - \frac{r_e}{r_o}\right]$



APPENDIX A

DATA TABULATION

Data used in this analysis were obtained through a literature search from twenty-four technical reports. These results are tabulated in the form of nondimensional parameters obtained through the use of the data reduction procedure described in Appendix A.

A few comments regarding the explanation of this table are in order.

The reference from which the data were obtained, the symbol representing the data on the figures, dimensionless parameters, are listed reading from left to right.

Some of the parameters from various references could not be determined due to lack of sufficient information, for example the area ratio from Reference 12. This is indicated on the chart by the letters "NA" meaning not available.

The circulation ratio, $\frac{\Gamma_e}{\Gamma_{.8}}$, determined before the radius correction (see Appendix A) was made.

All reports except where otherwise noted had a specific heat ratio of 1.4.

Report, symbol	$\frac{\Gamma_e}{\Gamma_{.8}}$	$\frac{r_e}{r_o}$	$\frac{A_{ri}}{A_{re}}$	$\frac{L}{D}$	$\frac{v}{u}$	M_{tmax}	Re_r	A	$\frac{\mu^*}{\mu}$	Re_t	$\frac{v_{.8}}{v_j}$	$\frac{\dot{m}}{\dot{m}_{max}}$	$\frac{P_o}{P_{exh.}}$
Ref 2^a A	NA	NA	NA	6	NA	NA	NA	NA	2.7	$.01\times10^5$	NA	NA	NA
	NA	NA	NA	6	NA	NA	NA	NA	5.3	$.04\times10^5$	NA	NA	NA
	NA	NA	NA	6	NA	NA	NA	NA	3.4	$.05\times10^5$	NA	NA	NA
	NA	NA	NA	6	NA	NA	NA	NA	2.6	$.06\times10^5$	NA	NA	NA
	NA	NA	NA	6	NA	NA	NA	NA	4.3	$.12\times10^5$	NA	NA	NA
	NA	NA	NA	6	NA	NA	NA	NA	7.0	$.32\times10^5$	NA	NA	NA
Ref 5 B	NA	.35	.08	NA	NA	NA	NA	NA	NA	NA	NA	.082	NA
	NA	.35	.12	NA	NA	NA	NA	NA	NA	NA	NA	.094	NA
	NA	.35	.18	NA	NA	NA	NA	NA	NA	NA	NA	.107	NA
	NA	.35	.23	NA	NA	NA	NA	NA	NA	NA	NA	.126	NA
	NA	.35	.32	NA	NA	NA	NA	NA	NA	NA	NA	.151	NA
	NA	.25	.03	NA	NA	NA	NA	NA	NA	NA	NA	.081	NA
	NA	.25	.04	NA	NA	NA	NA	NA	NA	NA	NA	.083	NA
	NA	.25	.07	NA	NA	NA	NA	NA	NA	NA	NA	.093	NA
	NA	.25	.16	NA	NA	NA	NA	NA	NA	NA	NA	.122	NA
	NA	.25	.23	NA	NA	NA	NA	NA	NA	NA	NA	.147	NA
	NA	.25	.34	NA	NA	NA	NA	NA	NA	NA	NA	.173	NA
	NA	.25	.48	NA	NA	NA	NA	NA	NA	NA	NA	.192	NA
	NA	.25	.71	NA	NA	NA	NA	NA	NA	NA	NA	.230	NA
	NA	.15	.04	NA	NA	NA	NA	NA	NA	NA	NA	.141	NA

Report, symbol	$\frac{\Gamma_e}{\Gamma_{.8}}$	$\frac{r_e}{r_o}$	$\frac{A_{ri}}{A_{re}}$	$\frac{L}{D}$	$\frac{v}{u}$	M_{tmax}	Re_r	A	$\frac{\mu^*}{\mu}$	Re_t	$\frac{v_{.8}}{v_j}$	$\frac{\dot{m}}{\dot{m}_{max}}$	$\frac{P_o}{P_{exh.}}$
	NA	.15	.09	NA	NA	NA	NA	NA	NA	NA	NA	.147	NA
	NA	.15	.12	NA	NA	NA	NA	NA	NA	NA	NA	.156	NA
	NA	.15	.21	NA	NA	NA	NA	NA	NA	NA	NA	.175	NA
	NA	.15	.43	NA	NA	NA	NA	NA	NA	NA	NA	.213	NA
	NA	.15	.66	NA	NA	NA	NA	NA	NA	NA	NA	.232	NA
	NA	.15	.99	NA	NA	NA	NA	NA	NA	NA	NA	.263	NA
	NA	.075	.07	NA	NA	NA	NA	NA	NA	NA	NA	.286	NA
	NA	.075	.17	NA	NA	NA	NA	NA	NA	NA	NA	.286	NA
	NA	.075	.38	NA	NA	NA	NA	NA	NA	NA	NA	.294	NA
	NA	.075	.51	NA	NA	NA	NA	NA	NA	NA	NA	.304	NA
	NA	.075	.77	NA	NA	NA	NA	NA	NA	NA	NA	.345	NA
	NA	.075	.87	NA	NA	NA	NA	NA	NA	NA	NA	.385	NA
Ref 6 C	.845	.50	.263	12	277	1.4	1760	.227	400	4.87×10^5	.565	.445	4.50
	.810	.25	.048	6	543	1.1	595	.970	108	3.23×10^5	.276	.254	2.64
Ref 7 D	NA	NA	NA	NA	NA	NA	NA	NA	24	3.4×10^5	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA	39	3.5×10^5	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA	180	4×10^5	NA	NA	NA
	NA	NA	NA	NA	NA	NA	NA	NA	300	6×10^5	NA	NA	NA

Report, symbol		$\frac{\Gamma_e}{\Gamma_{.8}}$	$\frac{r_e}{r_o}$	$\frac{A_{ri}}{A_{re}}$	$\frac{L}{D}$	$\frac{v}{u}$	M_{tmax}	Re_r	A	$\frac{u^*}{\mu}$	Re_t	$\frac{v_{.8}}{v_j}$	$\frac{\dot{m}}{\dot{m}_{max}}$	$\frac{P_o}{P_{exh.}}$
Ref 8	E	.935	.52	NA	1.9	268	.10	2660	.205	475	$.712\times10^5$	NA	NA	NA
		.910	.52	NA	1.9	31	.11	2660	.229	593	$.823\times10^5$	NA	NA	NA
		.945	.52	NA	1.9	82	.107	930	.606	133	$.76\times10^5$	NA	NA	NA
		.808	.52	NA	1.9	43	.104	930	.682	175	$.865\times10^5$	NA	NA	NA
Ref 11	F	.515	.29	.08	.5	144	.65	8300	2.38	2130	12×10^5	.66	NA	NA
Ref 12	G	.95	.35	NA	.0835	6.5	.102	17000	1.03	1416	1.1×10^5	NA	NA	NA
		.685	.35	NA	.0835	18.8	.227	17000	2.40	2600	3.2×10^5	NA	NA	NA
Ref 14[b]	H	.85	.10	3.51	3	248	.37	419	1.11	44	1.04×10^5	NA	NA	NA
		.775	.10	3.51	3	486	.162	206	2.18	17.75	1.0×10^5	NA	NA	NA
		.62	.10	3.51	3	790	NA	114	3.64	10	$.9\times10^5$	NA	NA	NA
		.91	.10	3.51	3	325	NA	317	1.465	29.4	1.03×10^5	NA	NA	NA
		.90	.10	3.51	3	76.5	NA	675	.392	94	$.516\times10^5$	NA	NA	NA
Ref 15[b]	I	.57	.10	4.27	3	483	0	185	2.27	31	$.894\times10^5$	.73	NA	NA
		.437	.10	4.27	3	750	0	103	3.56	19.1	$.77\times10^5$	.695	NA	NA
		.44	.10	8.55	3	860	0	95	4.03	14.4	$.818\times10^5$	.665	NA	NA
Ref 16[b]	J	.325	.104	4.45	3.33	507	0	150	2.4	55.6	$.763\times10^5$	.73	NA	NA
		.264	.104	4.45	3.33	1116	0	60	5.5	18.8	$.67\times10^5$	.72	NA	NA
		.260	.104	4.45	3.33	1510	0	148	5.78	46	2.24×10^5	.705	NA	NA

Report, symbol		$\frac{\Gamma_e}{\Gamma_{.8}}$	$\frac{r_e}{r_o}$	$\frac{A_{ri}}{A_{re}}$	$\frac{L}{D}$	$\frac{v}{u}$	M_{tmax}	Re_r	A	$\frac{\mu^*}{\mu}$	Re_t	$\frac{v_{.8}}{v_j}$	$\frac{\dot{m}}{\dot{m}_{max}}$	$\frac{P_o}{P_{exh.}}$
Ref 17	K	.675	.14	.10	5.35	910	1.00	329	1.84	50.5	$3x10^5$	.098	.336	2.72
		.560	.14	.10	5.35	1245	.61	239	2.60	34.1	$2.97x10^5$	.119	.264	1.42
		.634	.14	.10	5.35	950	1.06	456	1.79	74	$4.33x10^5$	.105	.328	3.80
		.608	.14	.10	5.35	1020	.86	435	1.90	71	$4.44x10^5$	.104	.337	2.00
		.640	.14	.10	5.35	985	1.04	624	1.73	96	$6.15x10^5$	.0995	.328	5.22
		.665	.14	.10	5.35	1020	1.04	651	1.76	100	$6.64x10^5$	.0985	.320	2.69
Ref 19[d]	L	NA	NA	NA	4	2	NA	900	.015	12	$.018x10^5$	NA	NA	NA
		NA	NA	NA	2	5.7	NA	900	.07	25	$.051x10^5$	NA	NA	NA
		NA	NA	NA	5	10.8	NA	900	.04	30	$.097x10^5$	NA	NA	NA
Ref 20	M	.658	.20	.348	3	350	.20	256	1.60	46.5	$.895x10^5$	.595	.11	1.15
		.29	.20	.348	3	454	.45	1110	1.48	464	$5.04x10^5$	.640	.18	2.00
		.306	.20	.348	3	450	.47	1350	1.42	563	$6.07x10^5$	.617	.196	2.30
Ref 21	N	.92	.17	.60	.107	15	.455	26700	1.43	1490	$4x10^5$	.775	.154	1.41
Ref 23	O[a]	.828	.17	.544	2	193	0	270	1.48	30	$.522x10^5$	.475	.18	1.34
		.850	.17	.544	2	192	0	385	1.38	40.5	$.74x10^5$	.474	.179	1.68
		.930	.17	.544	2	184	0	535	1.24	51.8	$.985x10^5$	.454	.176	2.36
		.472	.17	.544	2	202	0	638	.82	60.8	$1.29x10^5$	.497	.159	3.39
		.71	.17	1.632	6	242	0	151	.67	32	$.366x10^5$	.60	.302	1.34
		.657	.17	1.632	6	310	0	218	.755	55.8	$.677x10^5$	.765	.302	1.68
		.765	.17	1.632	6	270	0	309	.63	65.8	$.835x10^5$	.67	.316	2.36
		.874	.17	1.632	6	233	0	412	.525	75	$.96x10^5$	.576	.308	3.39

Report, symbol	$\frac{\Gamma_e}{\Gamma_{.8}}$	$\frac{r_e}{r_o}$	$\frac{A_{ri}}{A_{re}}$	$\frac{L}{D}$	$\frac{v}{u}$	M_{tmax}	Re_r	A	$\frac{\mu^*}{\mu}$	Re_t	$\frac{v_{.8}}{v_j}$	$\frac{\dot{m}}{\dot{m}_{max}}$	$\frac{P_o}{P_{exh}}$
	.87	.17	2.72	10	191	.455	110	.40	18.5	$.21 \times 10^5$	.825	.368	1.34
	.775	.17	2.72	10	223	.455	159	.37	33.5	$.356 \times 10^5$	.55	.368	1.68
	.41	.17	2.72	10	224	.455	231	.346	36	$.515 \times 10^5$	.55	.378	2.36
	.642	.25	.256	2	247	.455	397	1.67	76	$.982 \times 10^5$	.446	.168	1.34
	.664	.25	.256	2	273	.455	542	1.70	93	1.48×10^5	.609	.129	1.68
	.79	.25	.256	2	238	.455	780	1.42	99	1.85×10^5	.586	.118	2.36
	.60	.25	.756	6	277	.455	288	.656	78	$.8 \times 10^5$	.682	.268	1.34
	.78	.25	.756	6	236	.455	417	.52	88	$.984 \times 10^5$	.586	.268	1.68
	.446	.125	1.01	2	288	.455	179	2.22	46	$.516 \times 10^5$	.708	.223	1.34
	.51	.125	1.01	2	267	.455	253	1.92	54	$.675 \times 10^5$	.655	.220	1.68
	.703	.125	1.01	2	206	.455	358	1.48	55	$.74 \times 10^5$	.508	.220	2.36
	.837	.125	1.01	2	182	.455	472	1.27	60	$.86 \times 10^5$	.45	.220	3.39
	.705	.125	3.02	6	226	.455	82	.715	14.9	$.185 \times 10^5$	.57	.360	1.34
	.65	.125	3.02	6	258	.455	122	.730	29	$.316 \times 10^5$	.65	.314	1.68
	.82	.125	3.02	6	222	.455	175	.600	29.2	$.388 \times 10^5$	.55	.320	2.36
	.90	.125	3.02	6	202	.455	233	.530	34.3	$.472 \times 10^5$	.50	.325	3.39
	.55	.125	5.04	10	350	.455	55.6	.685	16.8	$.194 \times 10^5$	.86	.345	1.34
	.75	.125	5.04	10	265	.455	84	.483	17.5	$.222 \times 10^5$	.65	.365	1.68
	.82	.125	5.04	10	244	.455	120	.42	20.7	$.294 \times 10^5$	.60	.367	2.36
	.89	.125	5.04	10	222	.455	164	.39	25	$.365 \times 10^5$	.55	.379	3.39

Report, symbol	$\frac{\Gamma_e}{\Gamma_{.8}}$	$\frac{r_e}{r_o}$	$\frac{A_{ri}}{A_{re}}$	$\frac{L}{D}$	$\frac{v}{u}$	M_{tmax}	Re_r	A	$\frac{\mu^*}{\mu}$	Re_t	$\frac{v_{.8}}{v_j}$	$\frac{\dot{m}}{\dot{m}_{max}}$	$\frac{P_o}{P_{exh}}$
Ref 24 P	.97	.5	.32	50	504	.62	278	.127	32.8	1.4×10^5	.246	NA	NA
	NA	NA	NA	6	317	NA	240	.65	60	$.75\times10^5$	NA	NA	NA
	NA	NA	NA	14	375	NA	240	.357	24	$.9\times10^5$	NA	NA	NA
	NA	NA	NA	50	500	NA	240	.113	21	1.2×10^5	NA	NA	NA
	NA	NA	NA	80	479	NA	240	.072	13	1.5×10^5	NA	NA	NA
	NA	NA	NA	10	342	NA	278	.407	45	$.95\times10^5$	NA	NA	NA
	NA	NA	NA	20	377	NA	278	.229	35	1.05×10^5	NA	NA	NA
	NA	NA	NA	40	485	NA	278	.134	26	1.35×10^5	NA	NA	NA
	NA	NA	NA	70	575	NA	278	.098	20	1.6×10^5	NA	NA	NA
	NA	NA	NA	100	700	NA	278	.072	15	1.95×10^5	NA	NA	NA
	NA	NA	NA	10	439	NA	205	.52	40	$.9\times10^5$	NA	NA	NA
	NA	NA	NA	30	488	NA	205	.19	22	1.0×10^5	NA	NA	NA
	NA	NA	NA	50	511	NA	205	.164	20	1.05×10^5	NA	NA	NA
	NA	NA	NA	60	535	NA	205	.103	17	1.10×10^5	NA	NA	NA
	NA	NA	NA	90	610	NA	205	.076	13	1.25×10^5	NA	NA	NA
	NA	NA	NA	100	535	NA	205	.061	11	1.10×10^5	NA	NA	NA
Ref 25 R	.756	.25	.154	6	289	.46	50	.456	9.1	$.145\times10^5$	.12	NA	NA
	.710	.25	.077	6	327	.52	50	1.05	10.2	$.164\times10^5$	.12	NA	NA
	.756	.25	.39	15	446	.42	50	.544	10.4	$.223\times10^5$	.18	NA	NA
	.725	.25	.195	15	427	.56	50	.523	10.6	$.214\times10^5$	.174	NA	NA

Report, symbol		$\frac{\Gamma_e}{\Gamma_{.8}}$	$\frac{r_e}{r_o}$	$\frac{A_{ri}}{A_{re}}$	$\frac{L}{D}$	$\frac{v}{u}$	M_{tmax}	Re_r	A	$\frac{\mu^*}{\mu}$	Re_t	$\frac{v_{.8}}{v_j}$	$\frac{\dot{m}}{\dot{m}_{max}}$	$\frac{P_o}{P_{exh}}$
		.817	NA	.256	10	358	.47	50	.68	8.8	$.179 \times 10^5$	.185	NA	NA
		.938	NA	.51	20	400	.42	50	.37	6.67	$.2 \times 10^5$	.16	NA	NA
Ref 26	**S**	.503	.14	.10	5.35	1075	.51	108	2.64	22.5	1.16×10^5	.122	.256	1.31
		.58	.14	.10	5.35	990	1.00	595	1.76	119	5.9×10^5	.113	.324	3.70
Ref 27[c]	T	.695	.134	.376	2.8	355	1.18	4050	1.00	810	14.4×10^5	.527	.251	7.75
Ref 28	U	.57	.14	.10	5.35	1315	1.00	595	2.26	112	7.84×10^5	.118	.324	3.70
Ref 29	V	.62	.14	.10	5.35	1090	.49	142	2.50	19	1.54×10^5	.111	.167	1.34
		.595	.14	.10	5.35	1200	1.08	1315	1.74	303	15.8×10^5	.123	.41	6.56
Ref 30	W	.845	.129	.885	2.56	318	1.00	1730	1.19	192	5.5×10^5	.595	.398	8.02
Ref 31	X	NA	.12	.0394	NA	NA	NA	NA	NA	NA	NA	NA	.116	NA
		NA	.12	.084	NA	NA	NA	NA	NA	NA	NA	NA	.152	NA
		NA	.12	.125	NA	NA	NA	NA	NA	NA	NA	NA	.149	NA
		NA	.12	.170	NA	NA	NA	NA	NA	NA	NA	NA	.167	NA
		NA	.12	.170	NA	NA	NA	NA	NA	NA	NA	NA	.182	NA
		NA	.12	.260	NA	NA	NA	NA	NA	NA	NA	NA	.208	NA
		NA	.12	.424	NA	NA	NA	NA	NA	NA	NA	NA	.250	NA
Ref 39	Y[a]	.72	.25	.062	6	246	.5	20	.9	2	$.049 \times 10^5$	NA	NA	NA

[a] The ratio of specific heats, γ, for the first 3 points from Ref. 2 is 1.67 (helium) and for the last 3 points 1.4 (nitrogen). The ratio of specific heats for Ref. 39 is 1.67 (helium). The other reports (i.e. Refs. 15, 16, 20) used water as the working fluid for which the ratio of specific heats is defined as one.

[b] In these reports a peripheral bypass was employed which removed part of the flow from the vortex chamber during the experiments. The value of $\frac{A_{ri}}{A_{re}}$ is, therefore, in question.

[c] The vortex chamber geometry used in this report was unusual in that it had a maximum radius of $r = 1.875$ inches (used here as r_o) at its center and then tapered slightly toward both ends.

[d] Even though there were insufficient data in these reports to apply the theory of Ref. 2 (i.e. except for the first entry under Ref. 24) these points are included because the boundary layer correction factor is of an order of magnitude small enough such that results obtained here will not be affected.