To: Professor LaFleur
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Re: AE401, Nozzle Performance
Section: 10

Certification: ______________________________________

Revision Date:______________________________________

Summary

The main driver for flow production is a pressure gradient. During this experiment, a measure for flow, “Flow Parameter,” and thrust force produced by the nozzles will both be calculated theoretically and measured experimentally. This requires some knowledge about compressible flow theory. To accomplish this task, the experimental apparatus includes measurement devices for several important things including mass flow rate, reservoir pressure, and chamber pressure. In each case, the theoretical values are compared to the values obtained experimentally. Also, all of the values are tabulated in appendix A.

Task 1:

This task is simply calculating the pressure ratio between the reservoir and the chamber. This is the vehicle by which the air is forced through the nozzle. The apparatus has a gauge for each of these two pressures, and the pressure ratio is calculated simply by $P_r = \frac{P_{supply}}{P_{Chamber}}$.

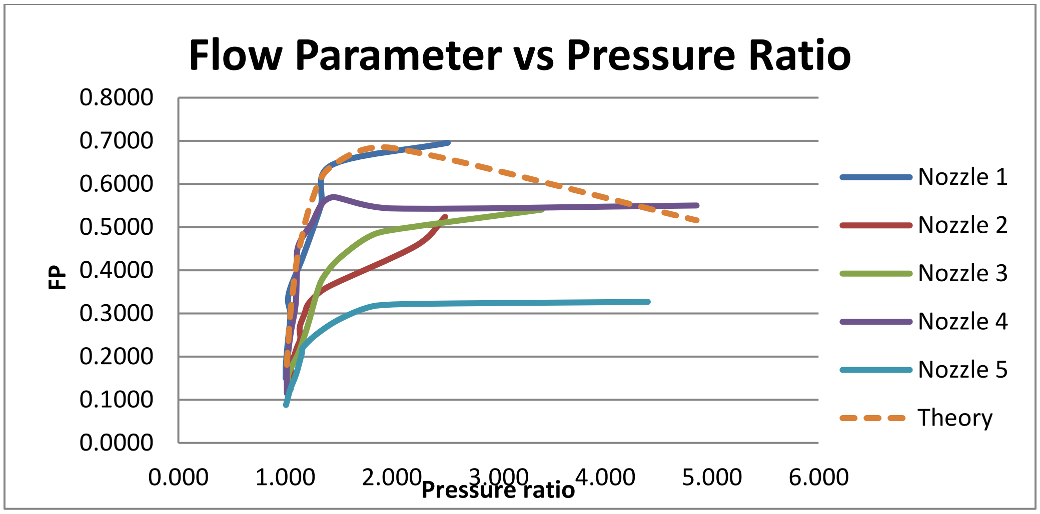
Task 2:

The mass flow rate can also be recorded with the apparatus. The air is released from the nozzle and into a chamber where the flow is directed upward at a float. The float deflection is recorded in centimeters and this measurement is converted to mass flow rate using a calibration curve. Assuming standard temperature and pressure, the calibration curve is as follows:

$$\dot{m}_{STD}\left[\frac{gram}{sec}\right] = 0.887 + 0.292\left[\frac{gram}{sec}\frac{1}{cm}\right]RM[cm] + 0.00234\left[\frac{gram}{sec}\frac{1}{cm^2}\right]RM^2[cm^2]$$

Task 3:

The following plot shows the Flow Parameter, FP, plotted against the pressure ratio between the reservoir and the chamber. Data is lacking for a couple of the nozzles, but it is easy to see the critical point at which a higher pressure ratio no longer correlates with a higher flow parameter. Also, a theoretical calculation of the flow parameter is included. This theoretical curve also reaches a critical point at a similar pressure ratio to that of the measurement data.



Task 4:

A theoretical nozzle thrust can be calculated from air properties and nozzle geometry. The first step is to calculate the exit velocity of the nozzle, which can be accomplished with the following formula. The calculated exit velocities are tabulated in Appendix A.

$$V^2 = 2h_0\left(1 - \frac{h}{h_0}\right) = 2C_P T_0\left(1 - \frac{1}{Tr}\right) = \frac{2}{\gamma_T} R T_0\left(1 - \frac{1}{Pr^{\gamma_T}}\right)$$

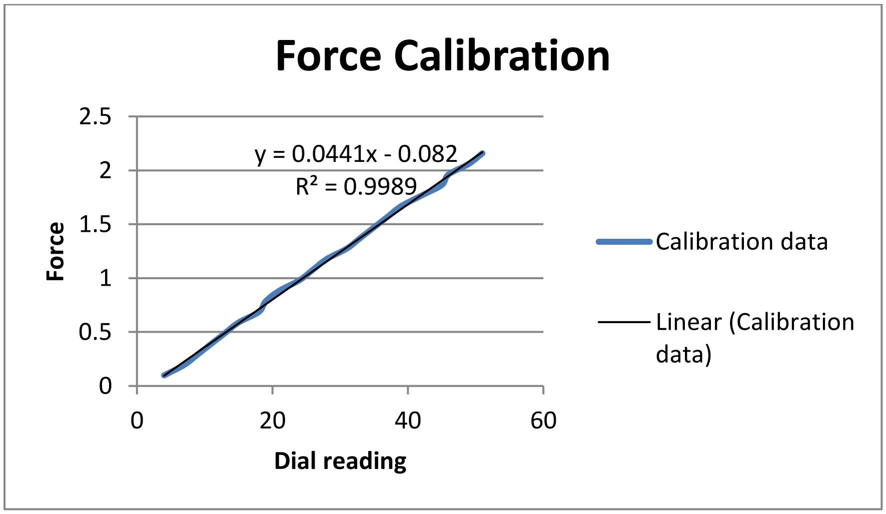
Task 5:

From the exit velocity, the theoretical thrust force can be calculated. It is important to note that converging-diverging nozzles will produce a higher thrust force than the theory predicts. The theoretical thrust force can be calculated as follows. Again, the thrust force is tabulated in appendix A.

$$F_{thrust} = \dot{m}\Delta V + \Delta p A_{exit}$$

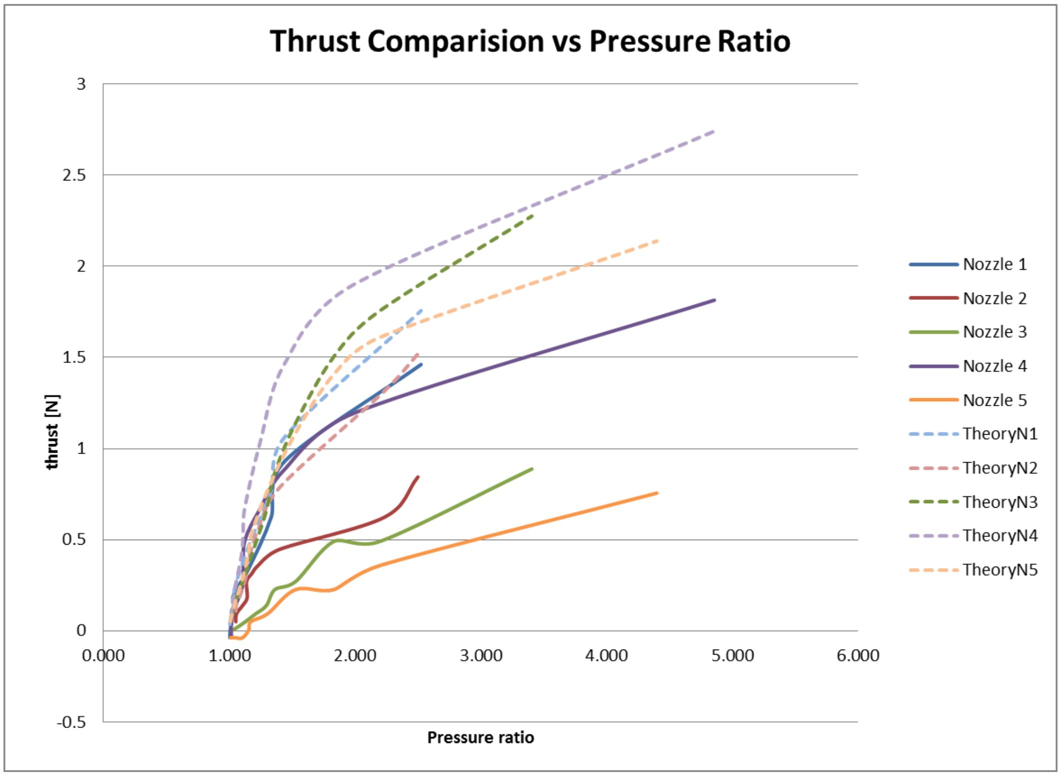
Task 6:

To measure the thrust force, the deflection of the nozzle support beam is calibrated with known weights. For the forces we are dealing with, a linear deflection is assumed and the curve fit works well. In this manner, the dial reading on the apparatus can easily be converted into force.



Task 7:

Here, the theoretical thrust we calculated and the thrust we measured using the apparatus are compared. The dotted lines are the theoretical values, while the solid lines are the measured values.



Appendix A

nozzle #	test	p1	p2	RM(cm)	M.	Dial reading	Pressure ratio	thrust [N]	FP	FP theory	V	Fthrust[N]
Nozzle 1	1	600	597	1.1	0.001211	1	1.005	-0.0379	0.1499	0.0997	29.1726	0.0353
	2	600	595	2.0	0.001480	2	1.008	0.0062	0.1833	0.1285	37.6842	0.0558
	3	555	540	3.0	0.001784	4	1.028	0.0944	0.2388	0.2291	68.0957	0.1214
	4	525	500	4.0	0.002092	6	1.050	0.1826	0.2960	0.3006	90.7311	0.1898
	5	555	540	5.2	0.002469	6	1.028	0.1826	0.3304	0.2291	68.0957	0.1680
	6	570	540	6.2	0.002787	7	1.056	0.2267	0.3632	0.3152	95.4759	0.2660
	7	525	450	7.0	0.003046	10	1.167	0.359	0.4309	0.4919	160.0701	0.4872
	8	480	360	8.5	0.003538	16	1.333	0.6236	0.5475	0.6052	216.6183	0.7659
	9	505	350	11.0	0.004382	23	1.443	0.9323	0.6446	0.6421	243.1863	1.0651
	10	505	200	12.0	0.004728	35	2.525	1.4615	0.6954	0.6583	371.8469	1.7569
Nozzle 2	1	605	575	1.0	0.001181	3	1.052	0.0503	0.1245	0.3064	92.6206	0.1093
	2	550	520	2.1	0.001511	4	1.058	0.0944	0.1750	0.3205	97.2310	0.1467
	3	525	475	3.0	0.001784	5	1.105	0.1385	0.2166	0.4136	129.4749	0.2308
	4	577	505	4.3	0.002186	6	1.143	0.1826	0.2415	0.4650	149.0627	0.3255
	5	580	510	5.1	0.002437	8	1.137	0.2708	0.2678	0.4584	146.4785	0.3567
	6	590	500	6.1	0.002755	9	1.180	0.3149	0.2976	0.5052	165.7317	0.4562
	7	590	480	6.9	0.003013	10	1.229	0.359	0.3255	0.5463	184.5102	0.5555
	8	595	425	8.0	0.003373	12	1.400	0.4472	0.3613	0.6299	233.4653	0.7866
	9	525	235	9.2	0.003771	16	2.234	0.6236	0.4579	0.6750	349.3182	1.3161
	10	500	200	10.2	0.004109	21	2.500	0.8441	0.5238	0.6599	370.0956	1.5193
Nozzle 3	1	600	585	1.5	0.001330	2	1.026	0.0062	0.1202	0.2206	65.4681	0.0870
	2	600	580	3.0	0.001784	2	1.034	0.0062	0.1612	0.2535	75.7113	0.1350
	3	575	510	4.4	0.002217	3	1.127	0.0503	0.2091	0.4458	141.5494	0.3135
	4	545	450	6.0	0.002723	4	1.211	0.0944	0.2709	0.5325	177.9569	0.4841
	5	505	390	7.5	0.003209	5	1.295	0.1385	0.3445	0.5869	205.7269	0.6595
	6	545	400	9.5	0.003872	7	1.363	0.2267	0.3852	0.6169	224.2755	0.8677
	7	550	360	11.0	0.004382	8	1.528	0.2708	0.4320	0.6601	260.4204	1.1402
	8	550	300	12.5	0.004903	13	1.833	0.4913	0.4833	0.6843	307.5071	1.5062
	9	550	250	13.0	0.005078	13	2.200	0.4913	0.5006	0.6766	346.3308	1.7572
	10	545	160	14.0	0.005434	22	3.406	0.8882	0.5406	0.5992	419.1475	2.2754
Nozzle 4	1	600	590	1.9	0.001450	1	1.017	-0.0379	0.1149	0.1809	53.3737	0.0773
	2	560	550	4.0	0.002092	3	1.018	0.0503	0.1776	0.1872	55.2589	0.1156
	3	525	500	6.1	0.002755	5	1.050	0.1385	0.2495	0.3006	90.7311	0.2498
	4	500	455	8.0	0.003373	7	1.099	0.2267	0.3207	0.4033	125.7370	0.4238
	5	500	450	10.4	0.004177	9	1.111	0.3149	0.3971	0.4226	132.7946	0.5544
	6	505	450	12.3	0.004833	13	1.122	0.4913	0.4549	0.4386	138.8256	0.6706
	7	510	410	14.0	0.005434	17	1.244	0.6677	0.5065	0.5566	189.6039	1.0296
	8	505	350	15.7	0.006048	22	1.443	0.8882	0.5693	0.6421	243.1863	1.4699
	9	510	255	15.1	0.005830	29	2.000	1.1969	0.5434	0.6835	326.8640	1.9040
	10	510	105	15.3	0.005902	43	4.857	1.8143	0.5502	0.5158	464.8435	2.7412
Nozzle 5	1	575	570	1.5	0.001330	1	1.009	-0.0379	0.0880	0.1313	38.4972	0.0512
	2	550	525	3.0	0.001784	1	1.048	-0.0379	0.1233	0.2941	88.6095	0.1579
	3	525	475	4.4	0.002217	1	1.105	-0.0379	0.1606	0.4136	129.4749	0.2867
	4	520	450	6.3	0.002819	2	1.156	0.0062	0.2062	0.4800	155.1273	0.4368
	5	550	470	7.5	0.003209	3	1.170	0.0503	0.2218	0.4956	161.6033	0.5179
	6	555	425	9.0	0.003705	4	1.306	0.0944	0.2538	0.5925	208.9453	0.7730
	7	550	360	10.4	0.004177	7	1.528	0.2267	0.2887	0.6601	260.4204	1.0863
	8	550	300	11.6	0.004589	7	1.833	0.2267	0.3172	0.6843	307.5071	1.4093
	9	550	250	11.8	0.004658	10	2.200	0.359	0.3220	0.6766	346.3308	1.6111
	10	550	125	12.0	0.004728	19	4.400	0.7559	0.3268	0.5394	453.0290	2.1386

References

Figliola, R., & Beasley, D. (2010). Theory and design for mechanical measurements. (5 ed.).

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Lafleur, Ronald. (2011). AE401 Nozzle Performance Laboratory Manual.