686 Museum Rd.
Gainesville, FL 32611
16 June 2023

Ryan Rinzel
University of Florida Nuclear Sciences Building
1929 Stadium Rd., Room 0312
Gainesville, FL 32611

Dear Mr. Rinzel,

The objective of the fan performance experiment is to calculate flow and analyze flow parameters for both backwards inclined and radial impeller designs used in a centrifugal pump. The parameters being calculated are the fan head rise, efficiency, and annual cost; these values from five different operating speeds allow for comparison for sizing the fan for a fan/pipe system.

The fan system contains a centrifugal pump which intakes air through the inlet nozzle. Next, the air is drawn towards the impeller and driven radially outwards; this increases the speed of the air and, in turn, increases the stagnation pressure of the air. The principle used in the experiment is the energy equation, derived from the first law of thermodynamics by applying a control volume to the pump. By manipulating the energy equation and substituting in the continuity equation, head rise can be calculated using the difference in pressure from the inlet and outlet of the pump. The equations used to calculate air characteristics are derived by assuming a steady-state system and the flow is incompressible. Multiplying the head rise equation by the mass flow rate and gravitational acceleration yields an equation for water horsepower (WHP). Fan efficiency can then be determined by dividing WHP by the shaft horsepower. Finally, break horsepower (BHP) can be calculated by dividing WHP by the fan efficiency. By determining the head coefficient, power coefficient, and capacity coefficient, it is possible to use the data collected from the pump and scale it up to larger pump, if necessary.

The pump apparatus was equipped with a TecQuipment's Versatile Data Acquisition System (VDAS). The VDAS was collecting data from the motor drive and pressure displays used to calculate flow parameters. The procedure for testing the backwards inclined and radial impellers were identical. First, the impeller began at 1000 RPM and data was collected for 5 seconds at a slide valve position of 100%; the slide valve was then repositioned in decreasing increments of 10%. In between each slide valve reposition a 5 second idle period was required for stable operation. Once all the data was taken, the impeller speed was increased by 500 RPM and data was collected in the same way; this process was continued up to 3000 RPM for both impeller types. Additionally, safety glasses, hearing protection and closed toed shoes were required in the laboratory to ensure safety.

This experiment facilitated the comparison of backwards inclined and radial impeller design when enclosed in a centrifugal pump. The radial impeller generated up to 102.95 ± 1.07 m of head rise at a volumetric flow rate of 0.185 ± 0.001 m^3/s and the backwards inclined impeller generated up to 89.68 ± 0.97 m of head rise at a volumetric flow rate of 0.1711 ± 0.001 m^3/s. It was found that the max efficiency of the radial impeller was 69.38%, measured at a speed of 2500 RPM and a volumetric flow rate of 0.200 ± 0.001 m^3/s. The max efficiency for the backwards inclined impeller was 82.64% measured at 3000 RPM and a volumetric flowrate of 0.206 ± 0.001 m^3/s. The annual cost to operate a backwards inclined impeller would range from $4.00 to $97.09, increasing with impeller speed. It was found that the radial impeller produced a higher head rise and lower efficiency, compared to the backwards type; therefore, for sizing and designing the fan, the backwards inclined impeller should be chosen.

Sincerely,

Conor Bowman | Alex Carr | Allison Porras | David Reyes-Tobar

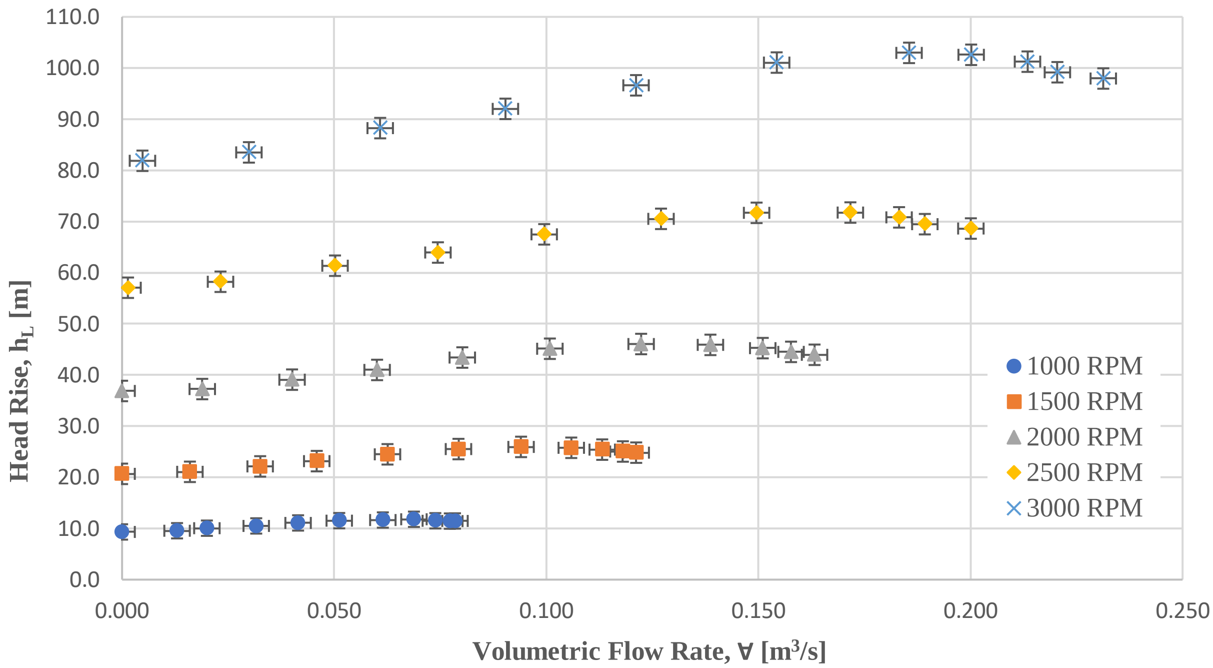

Figure 1: Fan head rise (h_L) versus the volumetric flow rate ($\dot{\forall}$) for a radial impeller ranging from 1000 RPM to 3000 RPM. At each RPM, data was collected at different air flows from 0% to 100%, at 10% increments. As the air flow increased, the volumetric flowrate increased causing an increase in head rise. This trend plateaus at an air flow between 60 and 70% and then decreases slightly as the air flow reaches 100%. The vertical error bars are associated with the error in head rise and the horizontal error bars are associated with the error in volumetric flow rate.

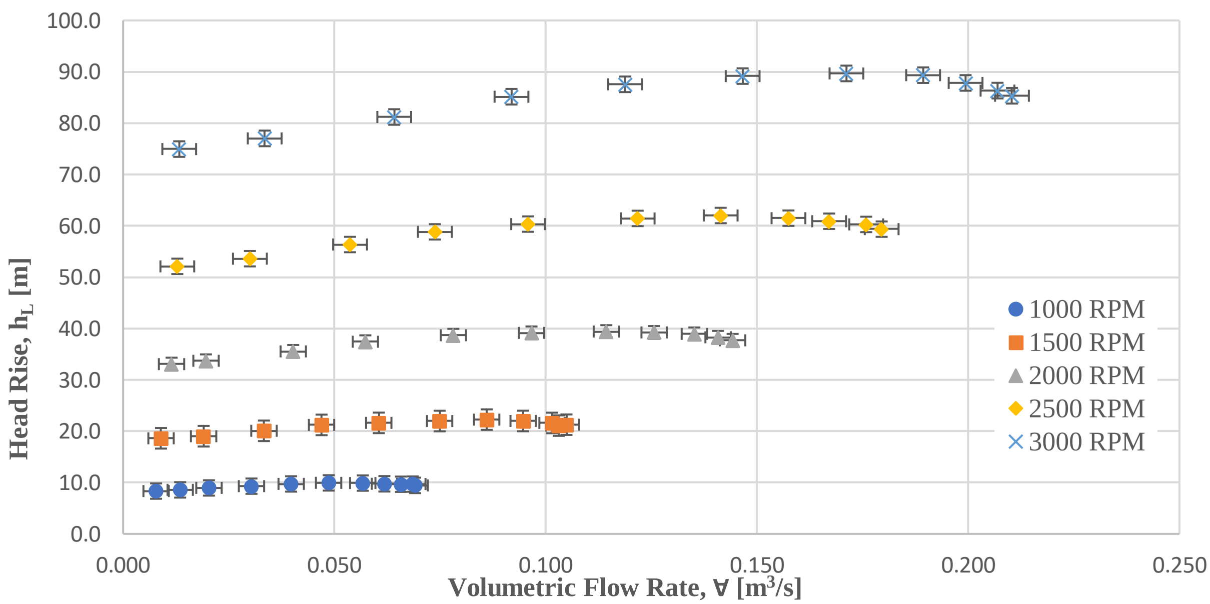

Figure 2: Fan head rise (h_L) versus the volumetric flow rate ($\dot{\forall}$) for a backwards inclined impeller ranging from 1000 RPM to 3000 RPM. At each RPM, data was collected at different air flows from 0% to 100%, at 10% increments. As the air flow increased, the volumetric flowrate increased causing an increase in head rise. This trend plateaus at an air flow around 60% and then decreases slightly as the air flow reaches 100%. The vertical error bars are associated with the error in head rise and the horizontal error bars are associated with the error in volumetric flow rate.

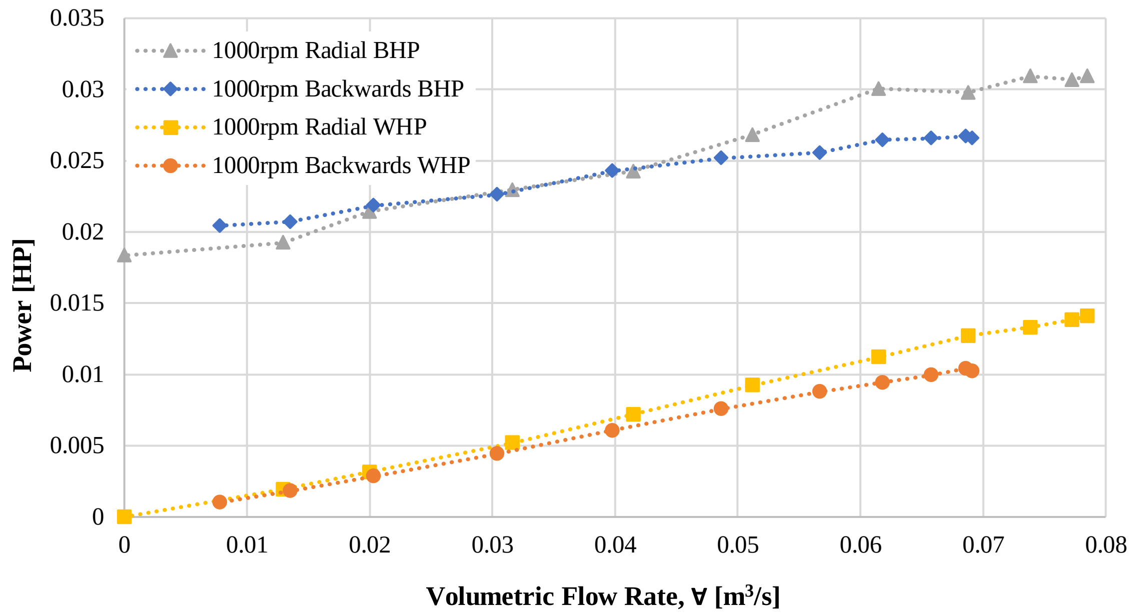

Figure 3: Fan water horsepower (WHP) and brake horsepower (BHP) curves in units of horsepower for both radial and backwards swept impeller at 1000rpm. The power is plotted as a function of volumetric flow rate which was changed during the experiment. Each point on the plot is the means of 11 values plotted over 5 seconds at that flow rate. As observed by the plot, BHP for both radial and backwards swept impellers were significantly higher than WHP produced. Another observation is that at higher flow rates, the radial impeller requires more BHP to achieve the same WHP, thus being less efficient.

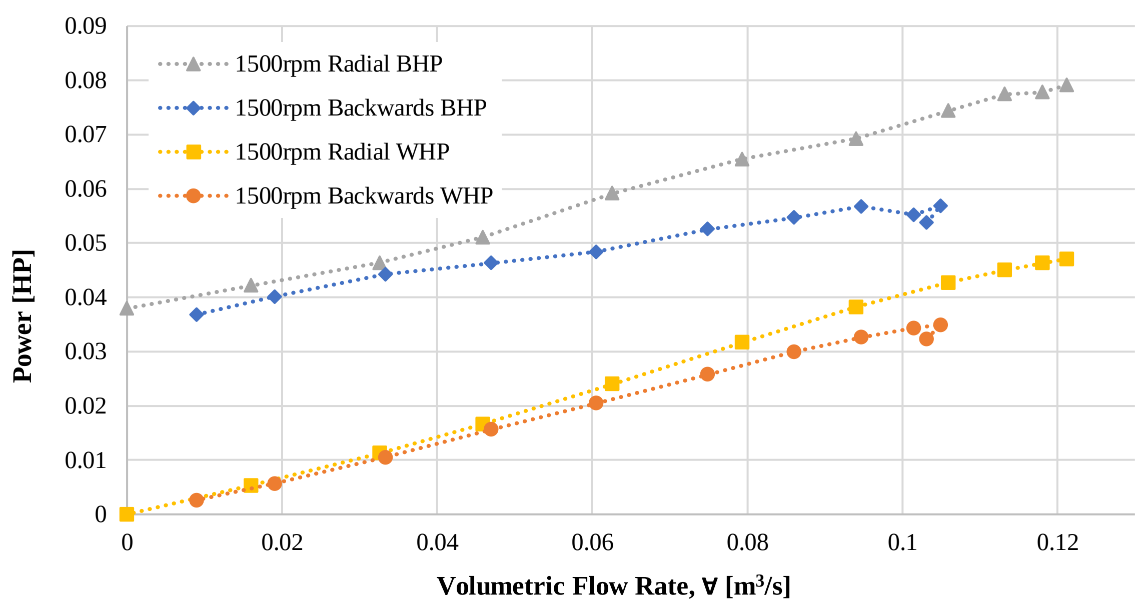

Figure 4: Fan water horsepower (WHP) and brake horsepower (BHP) curves in units of horsepower for both radial and backwards swept impeller at 1500rpm. The power is plotted as a function of volumetric flow rate which was changed during the experiment. Each point on the plot is the means of 11 values plotted over 5 seconds at that flow rate. A similar behavior between backwards and radial impellers can be observed as Figure 3.

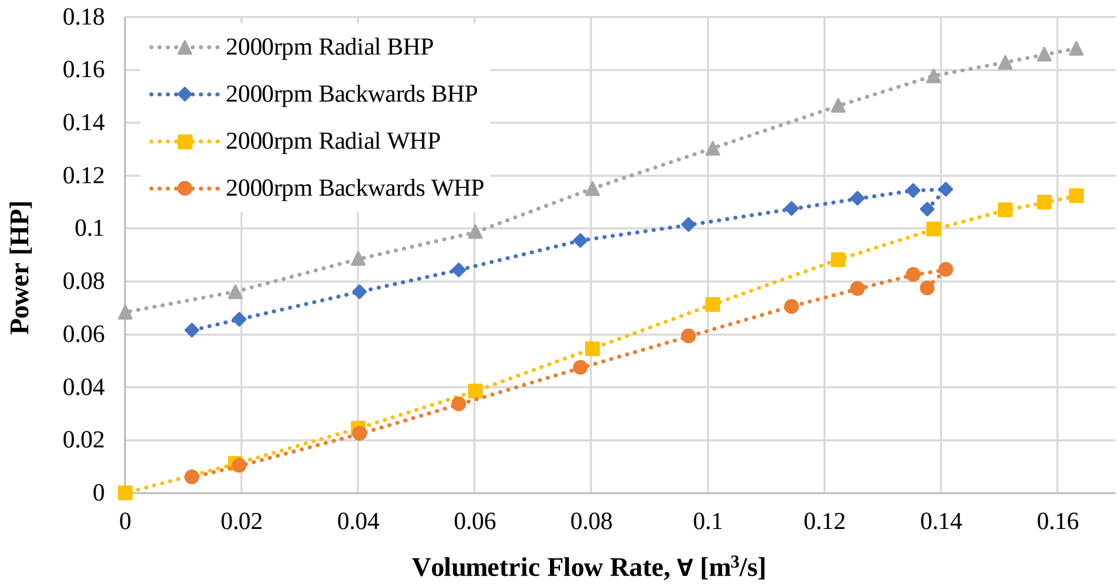

Figure 5: Fan water horsepower (WHP) and brake horsepower (BHP) curves in units of horsepower for both radial and backwards swept impeller at 2000rpm. The power is plotted as a function of volumetric flow rate which was changed during the experiment. Each point on the plot is the means of 11 values plotted over 5 seconds at that flow rate. A similar behavior between backwards and radial impellers can be observed as Figure 3. However, a new observation can be seen as rpm increases. With the higher rpm the radial and backwards BHP continue to diverge, demonstrating that the backwards swept impeller is more and more efficient as rpm increases.

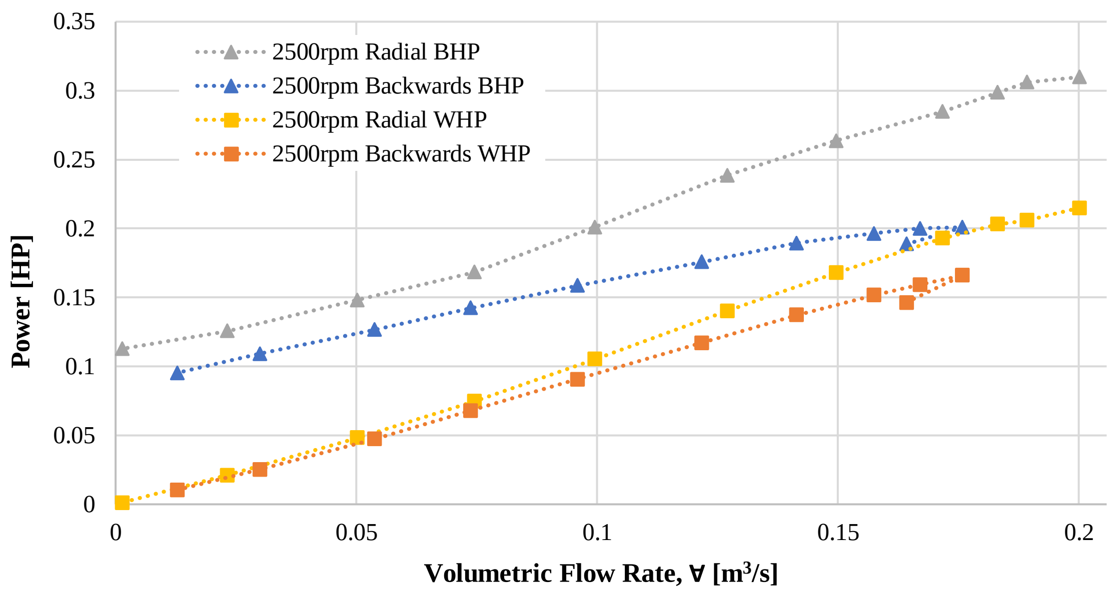

Figure 6: Fan water horsepower (WHP) and brake horsepower (BHP) curves in units of horsepower for both radial and backwards swept impeller at 2500rpm. The power is plotted as a function of volumetric flow rate which was changed during the experiment. Each point on the plot is the means of 11 values plotted over 5 seconds at that flow rate. A similar behavior between backwards and radial impellers can be observed as Figure 5.

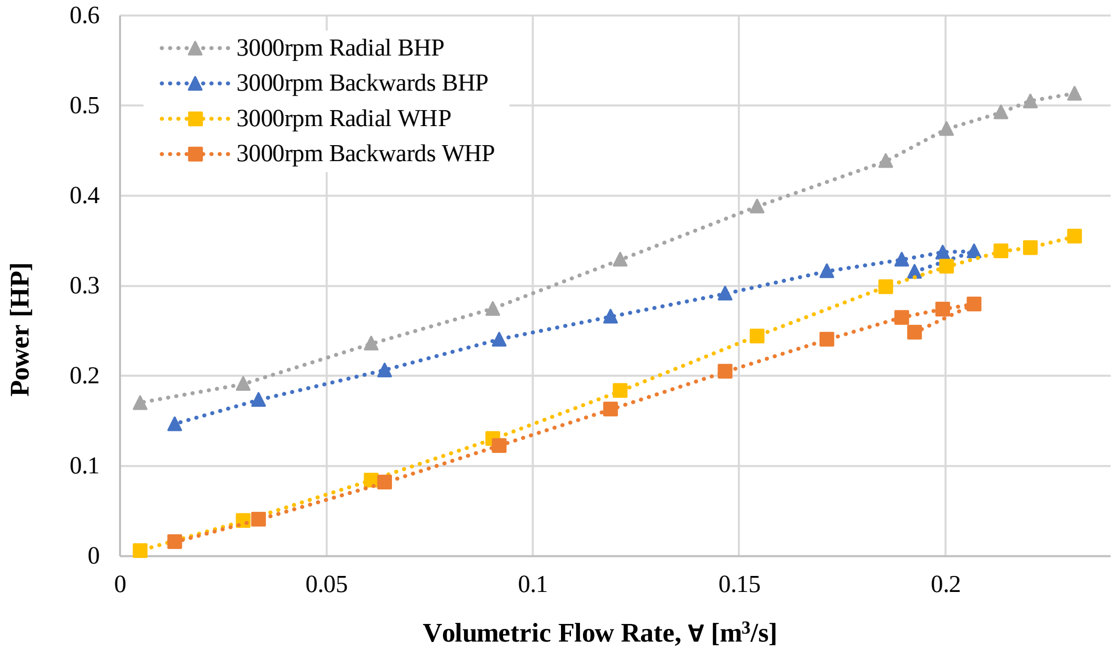

Figure 7: Fan water horsepower (WHP) and brake horsepower (BHP) curves in units of horsepower for both radial and backwards swept impeller at 3000rpm. The power is plotted as a function of volumetric flow rate which was changed during the experiment. Each point on the plot is the means of 11 values plotted over 5 seconds at that flow rate. A similar behavior between backwards and radial impellers can be observed as Figure 5.

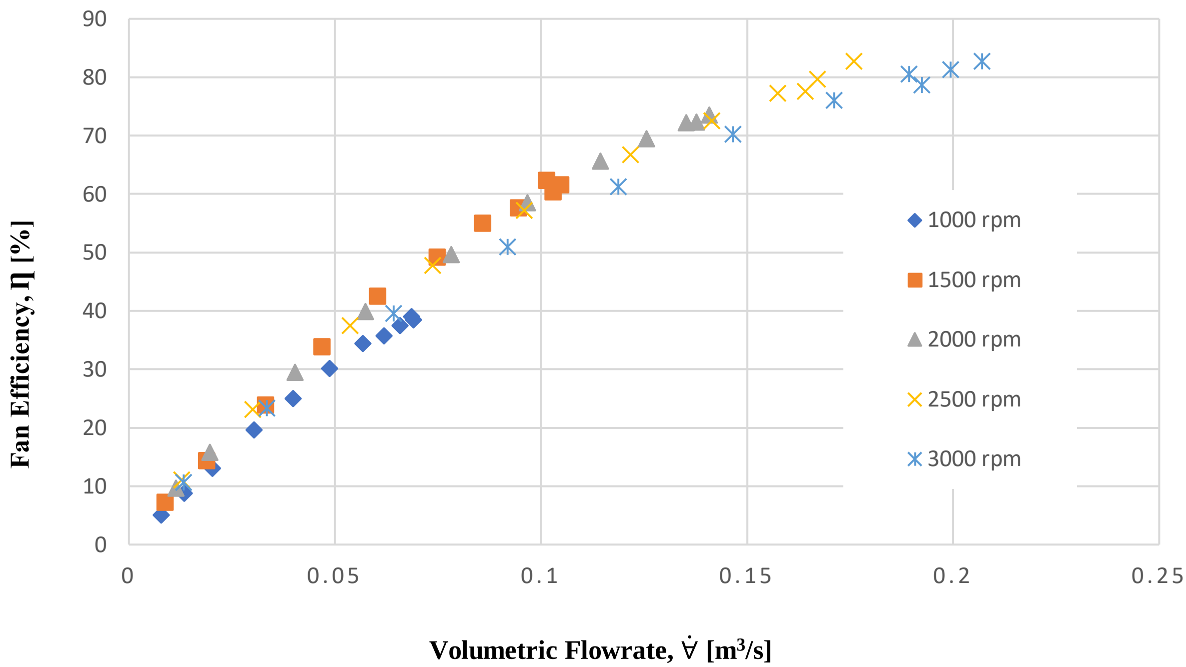

Figure 8: Fan efficiency curves on backwards impeller for five different impeller speeds. The efficiency of the fan is the ratio of the water horsepower (WHP), or the energy added to the flow, to the brake horsepower (BHP), or the power delivered to the centrifugal pump. WHP is dependent on the volumetric flowrate, which is plotted on the x-axis. The curve shows that the fan's efficiency increases with flowrate, and higher speeds correlate with greater flowrate.

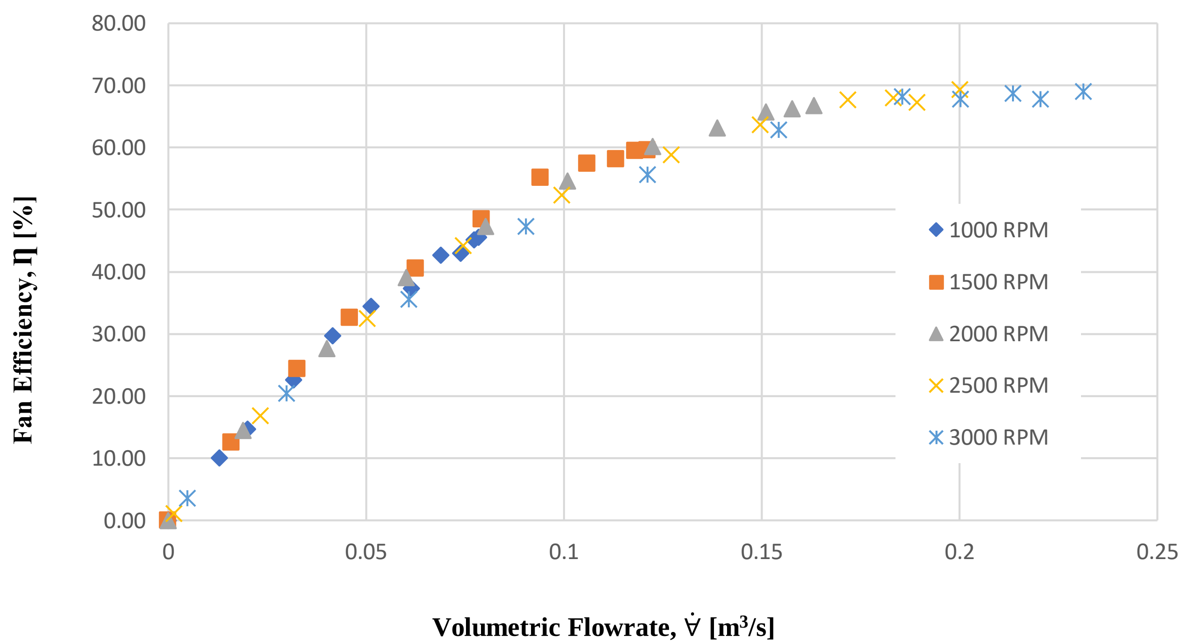

Figure 9: Fan efficiency curves on radial impeller for five different impeller speeds. The efficiency of the fan is the ratio of the water horsepower (WHP), or the energy added to the flow, to the brake horsepower (BHP), or the power delivered to the centrifugal pump. WHP is dependent on the volumetric flowrate, which is plotted on the x-axis. The curve shows that the fan's efficiency increases with flowrate, and higher speeds correlate with greater flowrate.

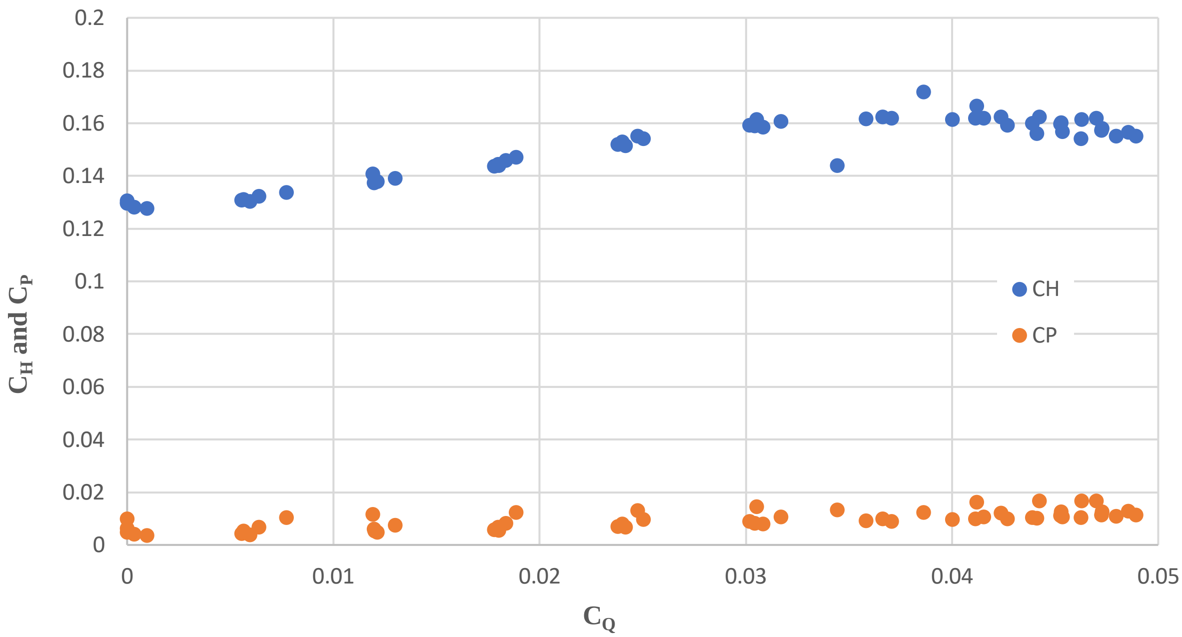

Figure 10: For the radial impeller, the head coefficient, C_H, and power coefficient, C_P, plotted against the capacity coefficient, C_Q. The head coefficient is an order of magnitude greater than the power coefficient. While the power coefficient remains constant, the head coefficient slightly increases as the capacity coefficient increases. The average of head available, break horsepower, and volumetric flowrate for each run were used to find the head coefficient, power coefficient, and capacity coefficient.

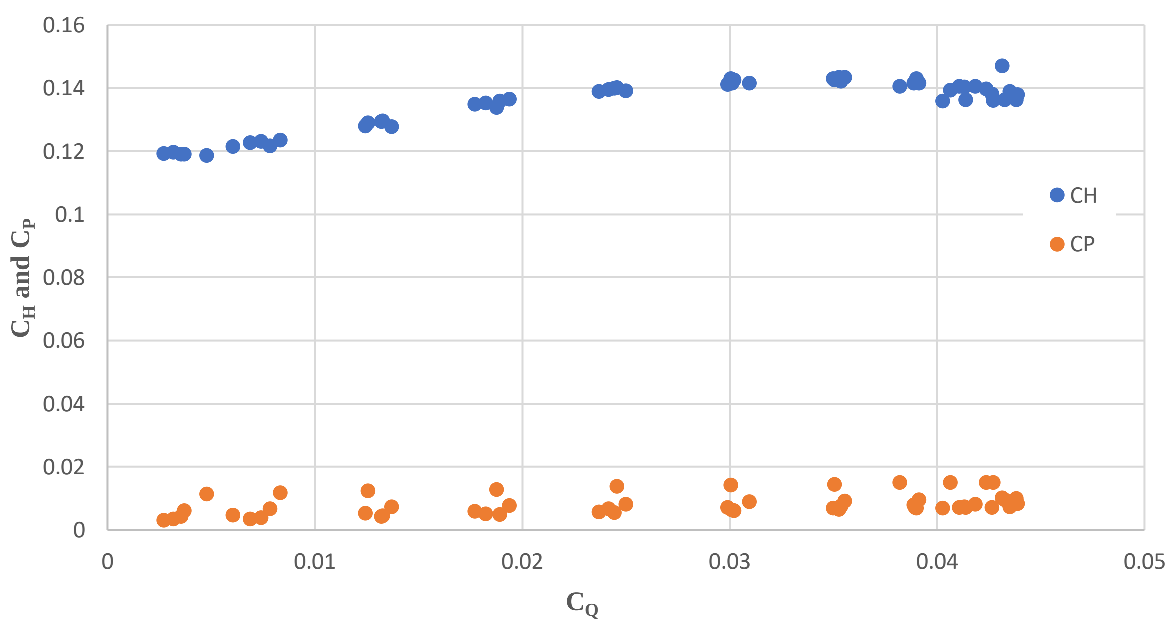

Figure 11: For the backwards swept impeller, the head coefficient, C_H, and power coefficient, C_P, plotted against the capacity coefficient, C_Q. The head coefficient is an order of magnitude greater than the power coefficient. While the power coefficient remains constant, the head coefficient slightly increases as the capacity coefficient increases. The average of head available, break horsepower, and volumetric flowrate for each run were used to find the head coefficient, power coefficient, and capacity coefficient.

Annual Cost Calculations

Table 1: The total annual cost to operate the backwards-facing impeller fan with the slide valve 100% open at five different RPM values. WHP was used to find BHP at 80% efficiency, then the energy utilized was calculated in kWh, since the fan was assumed to operate 2800 hours each year. Finally, the cost could be found with the value of $0.15 per kWh. The data shows that the annual cost increases with an increasing impeller speed, since the system is using more energy to support higher speeds.

	WHP [W]	BHP at 80% [W]	Electrical Power [kW]	Energy [kWh]	Annual Cost [$]
1000 rpm	7.620	9.525	0.0095	26.669	$ 4.00
1500 rpm	24.113	30.141	0.0301	84.396	$ 12.66
2000 rpm	57.802	72.253	0.0723	202.308	$ 30.35
2500 rpm	109.163	136.454	0.1365	382.071	$ 57.31
3000 rpm	184.940	231.175	0.2312	647.290	$ 97.09

Experimental Data

Tables 2: Radial Impeller Data

This table displays measured data for the radial impeller at five different speeds.

Fan Speed (rpm)	Slider Position (%)	Torque (Nm)	Total Power (W)	ΔP_1 (Pa)	P_2 (Pa)	P_3 (Pa)	Flow rate (m^3/s)	Mechanical Power Loss (W)	Head rise (m)	Fan efficiency (%)
1001	100	0.22	23.00	-206.0	-119.5	14.4	0.078	4	11.47	45.57
1001	90	0.22	22.82	-199.8	-115.1	18.3	0.077	4	11.44	45.12
1001	80	0.22	23.09	-182.5	-106.7	27.5	0.074	4	11.50	43.00
1001	70	0.21	22.18	-158.3	-94.1	43.6	0.069	4	11.79	42.68
1007	60	0.20	22.09	-126.3	-75.0	61.0	0.061	4	11.65	37.30
1005	50	0.19	20.00	-87.6	-54.8	79.7	0.051	4	11.52	34.44
1005	40	0.17	18.18	-57.6	-37.7	91.6	0.041	4	11.08	29.68
1005	30	0.16	17.27	-33.4	-24.0	98.5	0.032	4	10.49	22.63
1005	20	0.15	16.18	-13.4	-11.5	105.8	0.020	4	10.05	14.68
1005	10	0.14	14.64	-5.6	-2.3	109.3	0.013	4	9.55	10.08
1005	0	0.13	14.00	0.0	4.6	113.5	0.000	4	9.32	0.00
1497	100	0.37	59.64	-491.1	-263.8	25.9	0.121	5	24.80	59.52
1497	90	0.37	59.00	-466.2	-252.3	40.1	0.118	5	25.00	59.51
1498	80	0.36	58.60	-428.5	-234.6	62.0	0.113	5	25.40	58.13
1498	70	0.35	56.40	-374.9	-205.7	95.1	0.105	5	25.70	57.42
1461	60	0.34	51.50	-296.0	-164.3	138.5	0.094	5	25.90	55.16
1499	50	0.31	49.10	-210.4	-121.3	176.6	0.079	5	25.50	48.41
1499	40	0.28	44.30	-131.1	-79.4	206.5	0.063	5	24.50	40.57
1499	30	0.24	38.50	-70.5	-45.3	225.1	0.046	5	23.10	32.56
1500	20	0.22	35.80	-35.5	-24.5	233.9	0.033	5	22.10	24.34
1501	10	0.20	31.00	-8.6	-4.2	241.8	0.016	5	21.07	12.51
1501	0	0.18	28.00	0.0	11.9	253.3	0.000	5	20.68	0.00
2001	100	0.60	126.60	-891.4	-463.3	49.6	0.163	9	43.95	66.81
2001	90	0.59	125.00	-831.8	-437.3	82.4	0.158	9	44.52	66.29
2001	80	0.58	122.80	-762.9	-399.2	129.0	0.151	9	45.25	65.74
2002	70	0.56	117.10	-643.4	-342.9	192.7	0.139	9	45.89	63.18
2002	60	0.52	109.10	-500.9	-272.8	264.7	0.122	9	46.05	60.23
2002	50	0.46	98.70	-340.3	-194.4	332.5	0.101	9	45.13	54.65
2003	40	0.41	85.80	-215.2	-125.8	380.9	0.080	9	43.41	47.37
2004	30	0.35	75.10	-120.9	-73.8	404.6	0.060	9	40.99	39.07
2005	20	0.31	65.90	-53.6	-34.0	422.3	0.040	9	39.09	27.69
2005	10	0.27	57.00	-12.0	-1.5	433.4	0.019	9	37.25	14.50
2005	0	0.24	52.50	0.0	22.8	453.3	0.000	9	36.88	0.00
2502	100	0.88	231.45	-1339.8	-723.2	77.9	0.200	12	68.63	69.38
2502	90	0.87	228.45	-1198.6	-683.0	128.0	0.189	12	69.48	67.26
2502	80	0.85	224.00	-1122.9	-622.9	203.6	0.183	12	70.81	67.98
2503	70	0.81	214.00	-986.4	-533.8	303.7	0.172	12	71.75	67.74
2503	60	0.75	197.00	-748.5	-407.5	429.5	0.150	12	71.70	63.67
2504	50	0.68	177.64	-539.8	-297.6	525.5	0.127	12	70.52	58.81
2506	40	0.57	152.18	-331.5	-188.5	599.4	0.100	12	67.49	52.33
2508	30	0.48	127.09	-185.5	-107.8	638.5	0.074	12	63.94	44.26
2508	20	0.42	111.18	-84.4	-52.8	663.5	0.050	12	61.36	32.53
2509	10	0.36	95.36	-18.0	-2.3	677.4	0.023	12	58.22	16.84
2510	0	0.32	84.00	-0.4	37.5	703.5	0.001	12	57.06	1.11
2998	100	1.22	383.73	-1790.6	-1031.6	111.8	0.231	14	97.95	69.06
2997	90	1.20	378.00	-1626.6	-972.0	185.6	0.220	14	99.17	67.78
2998	80	1.17	369.00	-1524.6	-885.1	296.7	0.213	14	101.25	68.68
2999	70	1.13	353.64	-1340.4	-763.8	433.6	0.200	14	102.59	67.82
3000	60	1.04	329.27	-1151.6	-607.6	594.2	0.186	14	102.96	68.19
3002	50	0.92	292.09	-796.2	-425.5	754.3	0.154	14	101.07	62.89
3005	40	0.78	245.45	-490.9	-264.8	863.0	0.121	14	96.62	55.68
3007	30	0.65	205.27	-273.5	-157.4	916.7	0.090	14	92.02	47.36
3008	20	0.56	175.73	-123.8	-76.5	953.7	0.061	14	88.26	35.60
3010	10	0.45	145.00	-30.0	1.5	976.3	0.030	14	83.51	20.43
3011	0	0.40	127.82	-1.5	55.7	1011.4	0.005	14	81.87	3.61

Table 3: Backwards Impeller Data

This table displays measured data for the backwards swept impeller at five different speeds.

Fan Speed (rpm)	Slider Position (%)	Torque (Nm)	Total Power (W)	ΔP_1 (Pa)	P_2 (Pa)	P_3 (Pa)	Flow rate (m^3/s)	Mechanical Power Loss (W)	Head rise (m)	Fan efficiency (%)
1000	100	0.19	19.91	-158.00	-101.09	9.18	0.07	4	4.88	49.17
1000	90	0.19	20.00	-155.46	-97.82	15.45	0.07	4	4.94	50.00
1000	80	0.19	19.91	-142.91	-90.73	22.18	0.07	4	4.47	45.19
1000	70	0.19	19.82	-126.55	-79.09	34.82	0.06	4	4.07	44.89
1000	60	0.18	19.18	-106.55	-67.64	47.91	0.06	4	3.34	44.35
1000	50	0.18	18.91	-78.36	-50.27	65.73	0.05	4	2.41	40.26
1000	40	0.17	18.27	-52.36	-35.27	78.36	0.04	4	1.47	32.46
1000	30	0.16	17.09	-30.55	-20.09	88.45	0.03	4	0.90	22.95
1000	20	0.16	16.55	-13.64	-8.82	95.73	0.02	4	0.41	15.99
1000	10	0.15	15.73	-6.00	-2.00	98.09	0.01	4	0.34	8.52
1000	0	0.14	15.45	-2.00	5.18	102.55	0.01	4	0.62	8.74
1500	100	0.26	40.91	-355.82	-210.18	23.64	0.10	5	12.49	67.03
1500	90	0.27	43.00	-364.18	-213.46	34.82	0.10	5	12.92	68.40
1500	80	0.27	41.55	-340.73	-201.27	51.00	0.10	5	11.96	70.69
1500	70	0.27	43.00	-296.55	-180.46	76.27	0.09	5	9.95	63.91
1500	60	0.26	41.00	-244.91	-152.73	107.09	0.09	5	7.90	61.61
1500	50	0.25	40.00	-185.64	-115.91	140.73	0.07	5	5.98	54.30
1500	40	0.23	37.00	-121.09	-78.64	173.82	0.06	5	3.64	46.90
1500	30	0.22	35.45	-72.91	-48.91	198.91	0.05	5	2.06	39.15
1500	20	0.21	32.82	-36.73	-24.00	210.36	0.03	5	1.09	28.80
1500	10	0.19	30.00	-12.00	-6.00	216.09	0.02	5	0.51	16.00
1500	0	0.17	27.45	-2.73	9.91	227.27	0.01	5	1.08	8.92
2000	100	0.39	81.27	-641.46	-372.82	47.09	0.14	9	23.03	80.56
2000	90	0.41	85.82	-655.64	-375.73	71.18	0.14	9	24.00	81.76
2000	80	0.41	85.45	-604.91	-350.27	104.45	0.14	9	21.83	80.37
2000	70	0.40	83.27	-522.36	-304.91	153.09	0.13	9	18.64	77.72
2000	60	0.38	80.55	-432.73	-253.27	206.73	0.11	9	15.39	73.55
2000	50	0.36	77.09	-309.09	-183.64	273.36	0.10	9	10.76	64.62
2000	40	0.34	71.00	-202.00	-125.00	326.64	0.08	9	6.60	56.79
2000	30	0.30	63.00	-108.73	-70.64	366.27	0.06	9	3.27	46.30
2000	20	0.27	57.18	-53.64	-35.18	379.73	0.04	9	1.58	34.89
2000	10	0.23	50.73	-12.73	-7.73	385.82	0.02	9	0.43	18.31
2000	0	0.22	45.82	-4.36	17.00	403.00	0.01	9	1.83	11.36
2500	100	0.55	144.18	-969.46	-557.46	107.36	0.16	12	35.32	80.69
2500	90	0.57	151.55	-1023.4	-589.09	114.55	0.18	12	37.24	88.66
2500	80	0.57	149.91	-924.18	-547.64	163.18	0.17	12	32.28	86.12
2500	70	0.56	145.82	-820.55	-478.36	239.45	0.16	12	29.34	84.52
2500	60	0.54	141.73	-661.46	-387.64	336.27	0.14	12	23.48	78.96
2500	50	0.50	132.00	-490.73	-286.91	430.36	0.12	12	17.47	72.87
2500	40	0.45	119.64	-304.00	-182.09	522.27	0.10	12	10.45	62.68
2500	30	0.40	106.91	-180.00	-110.27	576.45	0.07	12	5.98	53.56
2500	20	0.36	96.00	-95.45	-63.00	594.91	0.05	12	2.78	42.03
2500	10	0.31	82.00	-29.82	-17.18	608.55	0.03	12	1.08	26.97
2500	0	0.27	72.18	-5.45	28.27	636.55	0.01	12	2.89	12.83
3000	100	0.76	239.91	-1331.8	-800.64	160.27	0.19	14	79.73	82.38
3000	90	0.80	254.82	-1416.7	-848.00	159.82	0.21	14	86.56	86.40
3000	80	0.80	251.00	-1315.2	-785.64	239.64	0.20	14	86.27	87.90
3000	70	0.78	245.27	-1186.3	-693.36	349.55	0.19	14	85.39	89.41
3000	60	0.75	237.00	-969.82	-568.73	478.18	0.17	14	80.33	89.75
3000	50	0.69	219.27	-711.27	-416.82	624.00	0.15	14	74.39	89.23
3000	40	0.63	199.00	-467.46	-272.46	749.73	0.12	14	65.58	87.63
3000	30	0.57	179.00	-279.64	-166.18	827.73	0.09	14	55.42	85.21
3000	20	0.49	155.73	-136.18	-85.45	862.36	0.06	14	42.83	81.26
3000	10	0.41	130.00	-37.09	-22.09	877.09	0.03	14	25.90	77.09
3000	0	0.35	112.18	-5.82	43.09	918.00	0.01	14	12.03	75.01

Sample Calculations

Density:

P_{atm} is atmospheric pressure, measured using a barometer; additionally, T is the temperature in the room, measured using a thermometer attached to the apparatus. P_{atm} was measured as 758.7 mmHg and converted to Pa, meanwhile T was measured as 23°C and converted to K for the calculations. The equation below uses the ideal gas law to find the density of air, the fluid utilized during this lab.

$$\rho_{air} = \frac{P_{atm}}{RT} = \frac{101151.7\ \cancel{Pa}}{287.05\ \frac{\cancel{Pa}\cdot m^3}{kg\cdot \cancel{K}}(296.15\ \cancel{K})} = 1.18988\frac{kg}{m^3}$$

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The uncertainty in density was calculated using the Root Sum Square (RSS) method and is dependent on the pressure and temperature variables, used in the ideal gas law. The uncertainty in pressure U_P is calculated using a value of ±0.02 mmHg, converted into Pa for the calculation; the uncertainty in temperature U_T is calculated using a value of ±0.5 K.

$$U_\rho = \sqrt{\left(\frac{\partial\rho}{\partial P}U_P\right)^2 + \left(\frac{\partial\rho}{\partial T}U_T\right)^2} = \sqrt{\left(\frac{1}{RT}U_P\right)^2 + \left(\frac{-P}{RT^2}U_T\right)^2}$$

$$U_P = \sqrt{\left(\frac{1}{287.05\ \frac{\cancel{Pa}\cdot m^3}{kg\cdot \cancel{K}} * 296.15\ \cancel{K}} * 2.67\ \cancel{Pa}\right)^2 + \left(\frac{-101151.7\ Pa}{287.05\ \frac{Pa\cdot m^3}{kg\cdot K} * (296.15\ K)^2} * 0.5\ K\right)^2}$$

$$U_\rho = 0.00201\frac{kg}{m^3}$$

Velocity:

The velocity of the fluid in the fan can be calculated from Bernoulli's equation, seen below.

$$P_a + \frac{1}{2}\rho V_a^2 = P_n + \frac{1}{2}\rho V_n^2$$

This can be rearranged to solve for Velocity (V_n) using terms pressure out P_a, pressure in P_n, and air density ρ_{air}.

$$V_n = \sqrt{\frac{2(P_a - P_n)}{\rho_{air}}} = \sqrt{\frac{2 * \Delta P}{\rho}}$$

One example calculation of WHP is 1000RPM at 100% open for the backwards swept impeller:

$$V = \sqrt{\frac{2 + 158\ Pa * \frac{\cancel{kg}}{\cancel{m} * s^2}}{1.29\frac{\cancel{kg}}{\cancel{m^3}}}} = 11.14\frac{m}{s}$$

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Volumetric flow rate:

Volumetric flow rate is equal to the product of velocity and inlet area, two values that can be further broken down. The inlet area is dependent on the diameter of the impeller, measured to be 248.992 mm; in this case, data was used for the backwards impeller at 1000 rpm with the slide valve 100% open. Velocity, as seen above, is dependent on the pressure differential and air density; the values used were 206 Pa and 1.189 kg/m^3, respectively.

$$\dot{\forall} = V_n * A_n = \frac{\pi D_n^2}{4}\sqrt{\frac{2 * \Delta P}{\rho_{air}}} = \frac{\pi(0.249\ m)^2}{4}\sqrt{\frac{2(206\ Pa)}{1.189\frac{kg}{m^3}}} = 0.906\frac{m^3}{s}$$

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The uncertainty in flow rate is dependent on the pressure differential, air density, and the impeller's diameter. In this calculation, the uncertainty in pressure U_P is calculated using a value of 0.25% of the pressure range (1000 – 3000 Pa); meanwhile, the uncertainty in air density is 0.00201 kg/m^3, calculated earlier in this section, and the uncertainty in diameter is 0.01 mm, which is equal to the precision of the calipers used to measure the impellers' geometries. The backwards impeller was used for this equation.

$$U_{\dot{\forall}} = \sqrt{\left(\frac{\partial\dot{\forall}}{\partial P}U_P\right)^2 + \left(\frac{\partial\dot{\forall}}{\partial \rho}U_\rho\right)^2 + \left(\frac{\partial\dot{\forall}}{\partial D}U_D\right)^2} = \sqrt{\left(\frac{\pi D^2}{4}\sqrt{\frac{1}{2\Delta P \cdot \rho}}U_P\right)^2 + \left(\frac{\pi D^2}{4}\sqrt{\frac{2\Delta P}{\rho^2}}U_\rho\right)^2 + \left(\frac{\pi D}{4}\sqrt{\frac{2\Delta P}{\rho}}U_D\right)^2}$$

$$= \sqrt{\left(\frac{\pi(0.249\ m)^2}{4}\sqrt{\frac{1}{2(206\ Pa)\left(1.189\frac{kg}{m^3}\right)}} * 5\ Pa\right)^2 + \left(\frac{\pi(0.249\ m)^2}{4}\sqrt{\frac{2(206\ Pa)}{\left(1.189\frac{kg}{m^3}\right)^2}} * 0.00201\frac{kg}{m^3}\right)^2 + \left(\frac{\pi(0.249\ m)}{4}\sqrt{\frac{2(206\ Pa)}{1.189\frac{kg}{m^3}}} * 1 \times 10^{-5}\ m\right)^2}$$

$$U_{\dot{\forall}} = 0.0111\frac{m^3}{s}$$

Head rise:

P_3 and P_2 are the outlet and inlet pressures within the fan respectively, ρ_{air} is the air density calculated previously, and g is the acceleration due to gravity. For this sample calculation, P_3 and P_2 were obtained from the backwards inclined 1000 RPM data at the 100% slide position. This set of data was chosen because it had the lowest uncertainty of all data sets. The equation below is an application of the energy equation for steady flow.

$$h_L = head\ loss = \frac{\Delta P}{\rho g} = \frac{P_3 - P_2}{\rho_{air} \cdot g} = \frac{9\left(\frac{\cancel{kg} * \boxed{m}}{\boxed{m^2} * \boxed{s^2}}\right) - (-110)\left(\frac{\cancel{kg} * m}{\boxed{m^2} * \boxed{s^2}}\right)}{1.18988\left(\frac{\cancel{kg}}{\boxed{m^3}}\right) * 9.81\left(\frac{\boxed{m}}{\boxed{s^2}}\right)} = 9.338\ m$$

$$h_a = \frac{\dot{Q}_{net,in}}{\dot{m}g} + \frac{\dot{W}_{shaft,net\ in}}{\dot{m}g} + \frac{(u_{in} - u_{out})}{g} + (z_{in} - z_{out})$$

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The uncertainty in head rise U_{hL} is dependent on the pressure difference ΔP between the fan's outlet and inlet, gravity, and air density. In this calculation, the uncertainty in the pressure differential $U_{\Delta P}$ is calculated using a value of ±0.25% of the pressure range (1000 to 3000 Pa), the uncertainty in the air density U_ρ is 0.00201 kg/m^3 as calculated earlier in this section, and the value used for uncertainty in gravity U_g is ±0.1 m/s^2. The equations below are utilizing data from the backwards impeller at 1000 rpm.

$$U_{h_L} = \sqrt{\left(\frac{\partial h_L}{\partial \Delta P} U_{\Delta P}\right)^2 + \left(\frac{\partial h_L}{\partial \rho} U_\rho\right)^2 + \left(\frac{\partial h_L}{\partial g} U_g\right)^2} = \sqrt{\left(\frac{1}{\rho g} U_{\Delta P}\right)^2 + \left(\frac{-\Delta P}{\rho^2 g} U_\rho\right)^2 + \left(\frac{-\Delta P}{\rho g^2} U_g\right)^2}$$

$$U_{h_L} = \sqrt{\left(\frac{1}{1.189\frac{kg}{m^3} * 9.81\frac{m}{s^2}} * 5\,Pa\right)^2 + \left(\frac{-109.645\,Pa}{\left(1.189\frac{kg}{m^3}\right)^2 * 9.81\frac{m}{s^2}} * 0.00201\frac{kg}{m^3}\right)^2 + \left(\frac{-109.645\,Pa}{1.189\frac{kg}{m^3} * \left(9.81\frac{m}{s^2}\right)^2} * 0.1\frac{m}{s^2}\right)^2}$$

$$U_{h_L} = 0.439\,m$$

Water Horsepower (WHP):

Water Horsepower (WHP) is the amount of power that goes into doing useful work, or the amount of energy which is added to the flow. WHP can be calculated using flow characteristics density(ρ), volumetric flow rate $(\dot{\forall})$, gravity (g), and head available (h_a). WHP can also be calculated using experimental data with pressure differential $(P_3 - P_2)$ and volumetric flow rate $(\dot{\forall})$.

$$WHP = \rho\dot{\forall}gh_a = (P_3 - P_2)\dot{\forall}$$

One example calculation of WHP is 1000RPM at 100% open for the backwards swept impeller:

$$WHP = (9.18Pa + 101.1) * 0.0691\frac{m^3}{s} = 7.62\,W = 7.62\,\cancel{W} * 0.00134\frac{HP}{\cancel{W}} = 0.0102\,HP$$

K. Schulze, "EML4147c – Turbomachinery 2 slides," University of Florida, Gainesville, FL, 2023.

Brake Horsepower (BHP) / Shaft Horsepower (W_s):

Brake horsepower (BHP), sometimes referred to shaft horsepower (W_s), is the power where it is delivered at the pump. This can be calculated using the equation below using shaft torque T, and rotation rate ω.

$$BHP = W_s = T \cdot \omega$$

One example calculation of WHP is 1000RPM at 100% open for the backwards swept impeller:

$$BHP = 0.189Nm * 1001\,\frac{rev}{min} * \frac{2*\pi}{60} = 19.81\,W = 19.81\,\cancel{W} * 0.00134\frac{HP}{\cancel{W}} = 0.027\,HP$$

K. Schulze, "EML4147c – Turbomachinery 3 slides," University of Florida, Gainesville, FL, 2023.

Fan Efficiency:

Fan efficiency is the ratio between the water horsepower (WHP) and the brake horsepower (BHP). These calculations used values from the radial impeller set up at 1000 rpm with the slide valve 100% open.

$$\eta_{fan} = \frac{WHP}{BHP} = \frac{\rho\dot{V}gh_a}{T\omega} = \frac{0.0141\,\cancel{HP}}{0.0309\,\cancel{HP}} = 0.4557 * 100\% = 45.57\%$$

K. Schulze, "EML4147c – Turbomachinery 2 slides," University of Florida, Gainesville, FL, 2023.

Head Coefficient:

Example calculation for the radial impeller at 1000 rpm with the slide valve 100% open.

$$C_H = \frac{gh_a}{\omega^2 D^2}$$

$$C_H = \frac{9.81 \frac{\cancel{m}}{\cancel{s^2}} * 11.471188\ \cancel{m}}{\left(1001\ \cancel{RPM} * \frac{2\pi \frac{rad}{\cancel{rev}}}{60 \frac{\cancel{s}}{\cancel{min}}}\right)^2 * (0.251598\ \cancel{m})^2} = 0.161784$$

K. Schulze, “EML4147c – Turbomachinery 5 slides,” University of Florida, Gainesville, FL, 2023.

Power Coefficient:

Example calculation for the radial impeller at 1000 rpm with the slide valve 100% open.

$$C_P = \frac{BHP}{\rho\omega^3 D^5} = \frac{T\omega}{\rho\omega^3 D^5} = \frac{T}{\rho\omega^2 D^5}$$

$$C_P = \frac{0.22\ \cancel{N \cdot m}}{1.18988 \frac{\cancel{kg}}{\cancel{m^3}} * \left(1001\ \cancel{RPM} * \frac{2\pi \frac{rad}{\cancel{rev}}}{60 \frac{\cancel{s}}{\cancel{min}}}\right)^2 * (0.251598\ \cancel{m})^5} = 0.0166900$$

K. Schulze, “EML4147c – Turbomachinery 5 slides,” University of Florida, Gainesville, FL, 2023.

Capacity Coefficient:

Example calculation for the radial impeller at 1000 rpm with the slide valve 100% open.

$$C_Q = \frac{\dot{\forall}}{\omega D^3}$$

$$C_Q = \frac{0.07848 \frac{\cancel{m^3}}{\cancel{s}}}{\left(1001\ \cancel{RPM} * \frac{2\pi \frac{rad}{\cancel{rev}}}{60 \frac{\cancel{s}}{\cancel{min}}}\right) * (0.251598\ \cancel{m})^3} = 0.0470083$$

K. Schulze, “EML4147c – Turbomachinery 5 slides,” University of Florida, Gainesville, FL, 2023.

Cost Calculations:

The annual cost to operate the backwards-facing impeller in the fan was dependent on the BHP, WHP, and other values given in the problem. At 1000 rpm with the slide valve 100% open, the WHP was 7.61W, divided by a motor efficiency of 80%. Additional values for this equation were 2800 operating hours per year and the relevant GRU rate of $0.15 per kWh.

$$BHP = \frac{WHP}{\eta} * 100\% = \frac{7.61\ W}{80\%} * 100\% = 9.525\ W$$

$$Annual\ Cost = 9.525\ \cancel{W}\left(\frac{1\ \cancel{kW}}{1000\ \cancel{W}}\right)\left(\frac{2800\ \cancel{hr}}{year}\right)\left(\frac{\$0.15}{\cancel{kWh}}\right) = \$4.00\ per\ year$$

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Lab Report Participation Log

Name	Date	Hours Worked	Description of Tasks Performed
Alli Porras	6/6/23	1	Set up report with sections + descriptions of each
Conor Bowman, Alex Carr, Alli Porras	6/9/23	1	Broke up report equally + went through data
Conor Bowman, Alex Carr, Alli Porras, and David Reyes-Tobar	6/14/23	2	Worked on sorting through data, calculating required parameters, making graphs, and writing out equations for sample calculations
Conor Bowman	6/14/23	2	Finished Graphs of Power vs Flow Rate
Alli Porras	6/14/23	3	Finished fan efficiency graphs and worked on sample calculations and uncertainty data
David Reyes-Tobar	6/14/23	3	Finished head, power and capacity coefficient calculations and compiled values for both impellers to plot values into graphs
Alli Porras	6/15/23	2	Continued work on sample calculations and uncertainty data; completed annual cost calcs
Conor Bowman	6/15/23	1	Started Sample calcs
Alex Carr	6/15/23	1	Started head rise graphs
Alli Porras	6/16/23	4	Finished uncertainty data, efficiency graph captions, sample calculations, data tables, and formatting before turning in
Conor Bowman	6/16/23	4	Finished captions, sample calcs, helped with data table
David Reyes-Tobar	6/16/23	2	Compiled all data values, both experimental and calculated, and organized them into their respective data table
Alex Carr	6/16/23	5	Finished head rise graphs, sample calcs, cover letter
	Total Hours:	31	