CAE 464/517 HVAC Systems Design

Spring 2023

March 23, 2023

Air distribution systems: Fan selection

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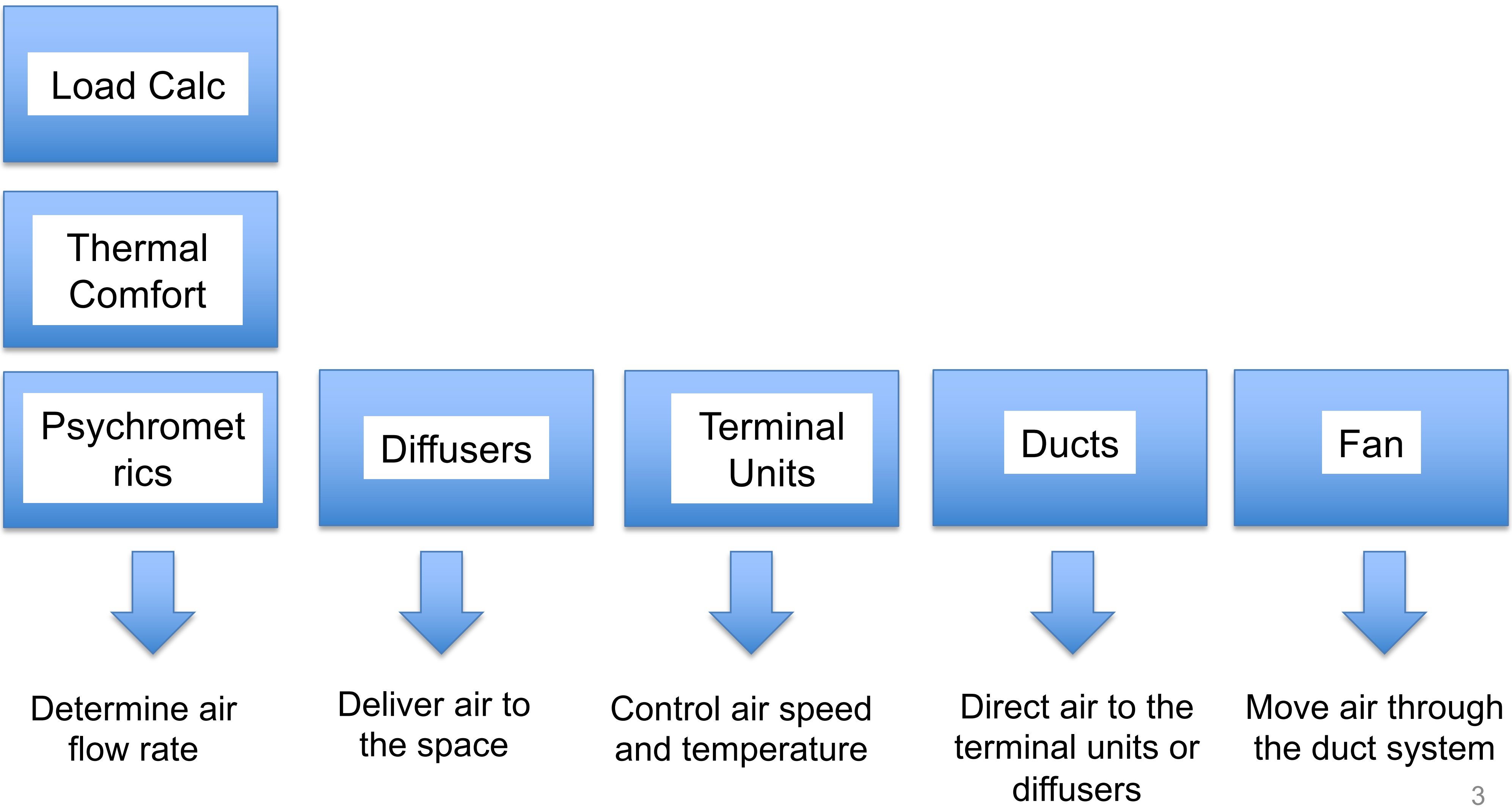
Dr. Mohammad Heidarinejad, Ph.D., P.E.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
muh182@iit.edu

RECAP

Recap

- There are a couple of components required for the design of an air distribution

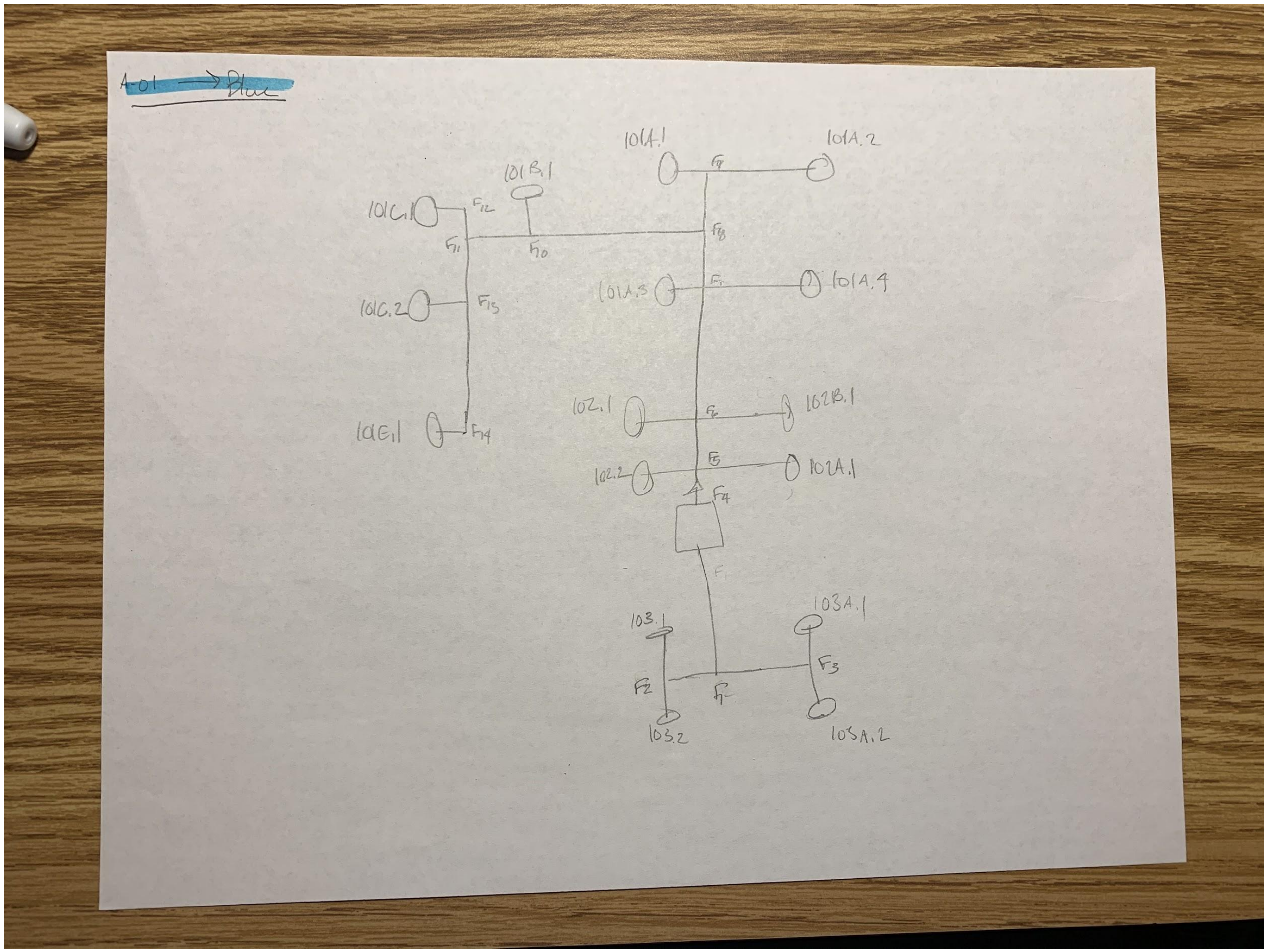


Recap

- First identify the zones being served by the air handling unit and color code the zones being served

Recap

- Then, add the schematic of the ductwork for zones being served by each AHU



Recap

- Using the calculated CFM, you need another value to start the equal friction method:
  - ❑ Duct diameter
  - ❑ Allowable velocity

Recap

- Construct a tabular format for the sections

Section	Air Flow Rate (cfm)	Duct Size (in)	Duct (in Rectangular)	Velocity (fpm)

Recap

- Calculate all the duct diameters, velocities and the section duct losses for the straight ductwork

Section	Air Flow Rate (cfm)	Duct (in Rectangular)	D_e (in)	Friction Loss (in/100 ft)	Length (ft)	Section Loss (in. w.c.)

Recap

- Identify the fittings and calculate the all the fitting losses

Section	Fitting No	Fitting Type	ASHRAE Fitting No.	Parameters	Loss Coefficient	Velocity (fpm)	P_v (in. w.c.)	P_t (in. w.c.)

Recap

- Identify the pressure loss summary for different paths and then size the fan best on the highest pressure drop and include balancing dampers for the other paths

ΔP (in. w.c.)

Path	Note	Duct	Tee	Duct	Tee	Damper	Duct	Outlet	Total	Differential
1	Path/Fitting Duct									
2	Path/Fitting Duct									
3	Path/Fitting Duct									

Recap

- Overall system resistance can be written as:

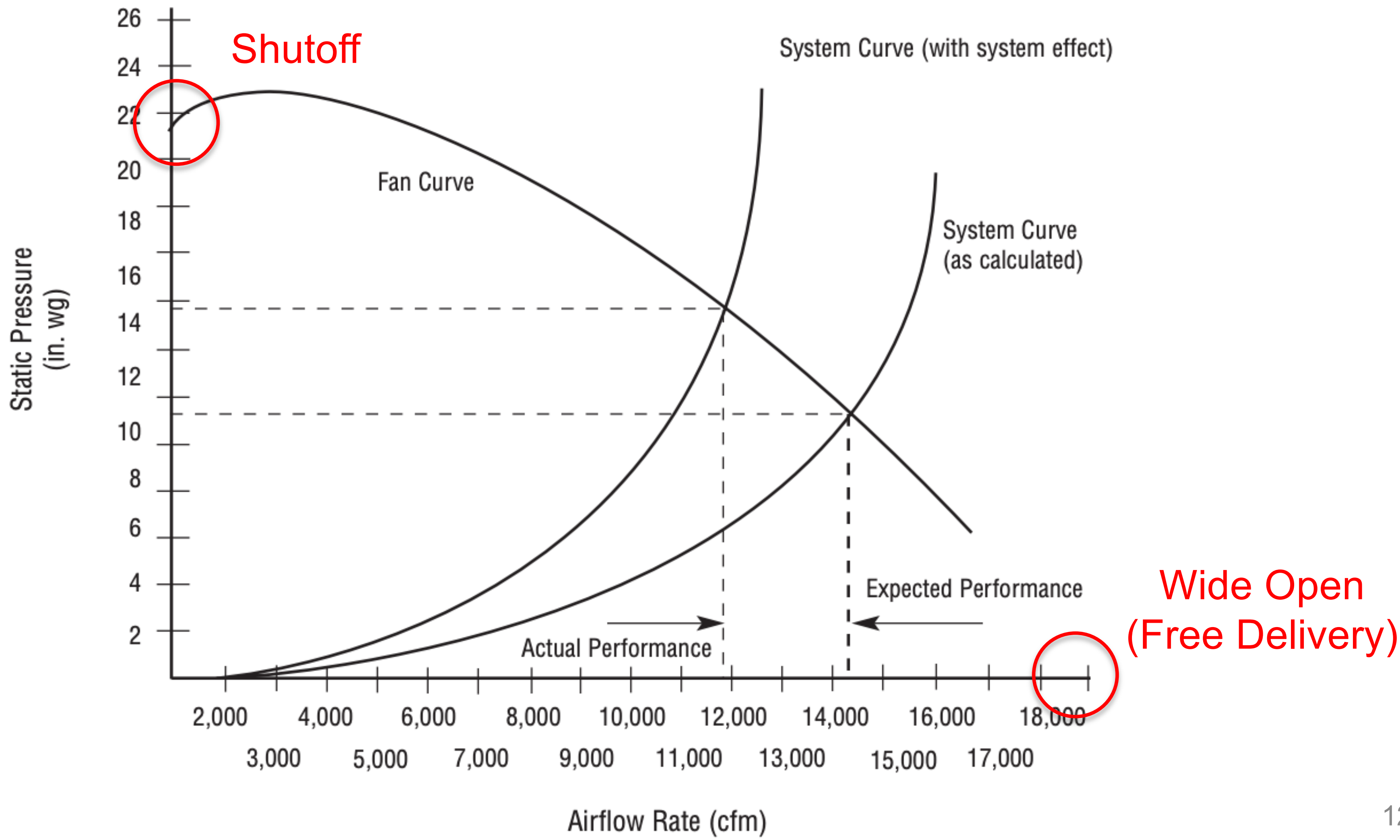
$$\Delta P_{total} = \sum \Delta P_{Ductwork} + \sum \Delta P_{fittings} =$$

$$= \sum f \frac{L}{D}\left(\frac{\rho V^2}{2g_c}\right) + \sum K \left(\frac{\rho V^2}{2g_c}\right)$$

$$\Delta P_{total} = (Constant) \times \dot{Q}^2$$

Recap

- This relationship defines the flow versus pressure characteristics of a system



https://www.nrel.gov/docs/fy03osti/29166.pdf

Recap

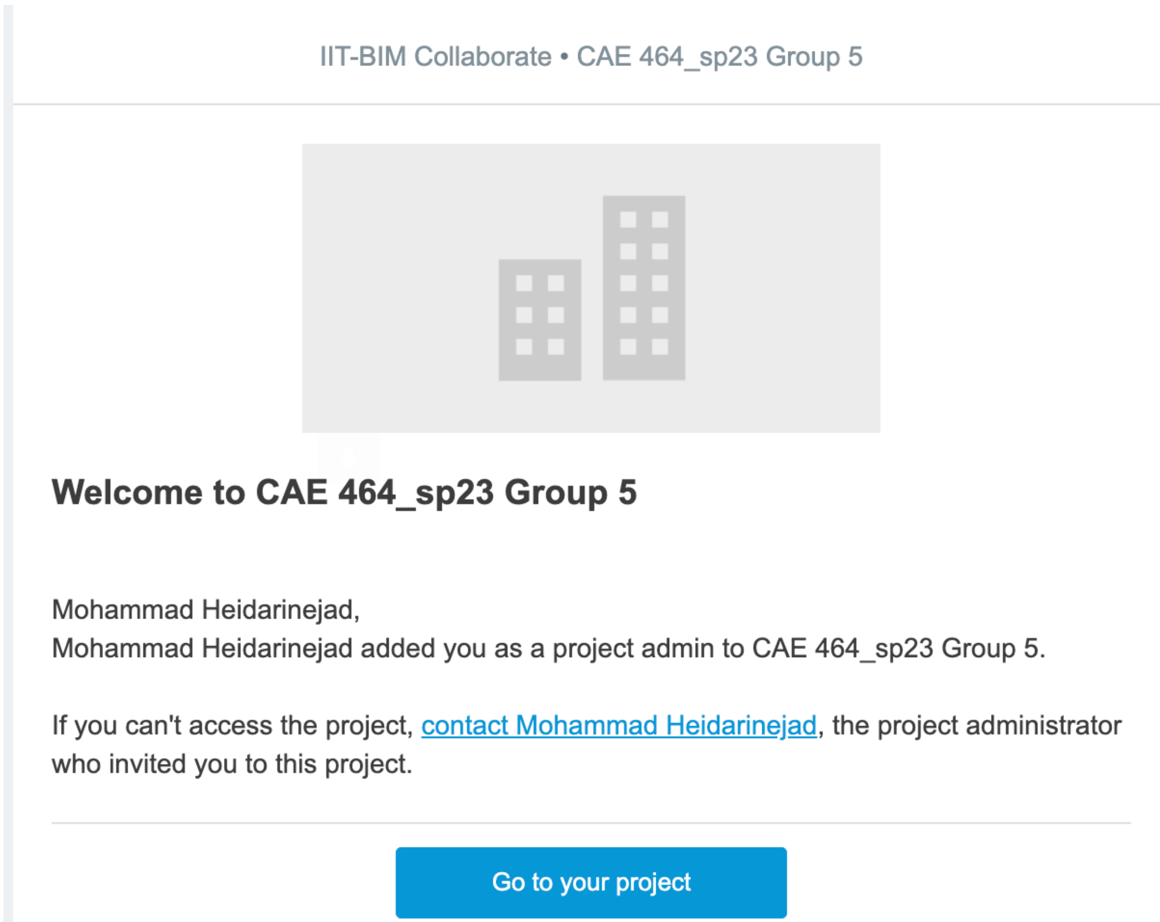
- System curve vs the fan curve

ANNOUNCEMENTS

Announcements

- Assignment 4 is posted (this coming Tuesday)

- Do not forget to work on Project Part 2



IIT-BIM Collaborate • CAE 464_sp23 Group 5

Welcome to CAE 464_sp23 Group 5

Mohammad Heidarinejad,
Mohammad Heidarinejad added you as a project admin to CAE 464_sp23 Group 5.

If you can't access the project, contact Mohammad Heidarinejad, the project administrator who invited you to this project.

Go to your project

Announcements

- Adding interesting and daily application of HVAC systems:

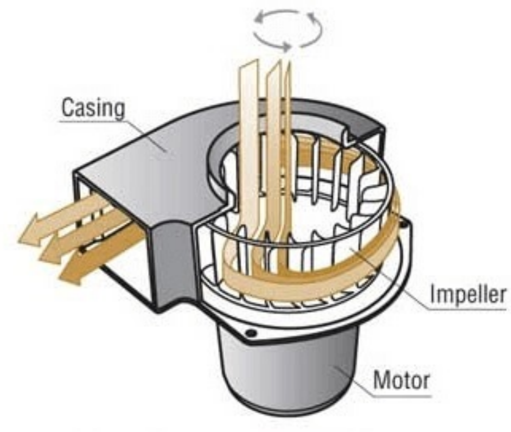
  https://docs.google.com/presentation/d/15bvvZ0VVm9SgonCzZ5N07MBvl0YdVRYaph6Z3evveJA/edit#slide=id.g1f2938fcdac_0_0

Announcements

CENTRIFUGAL FANS

Centrifugal Fans

- Fans are categorized as:
  - ❑ Radial (Centrifugal)



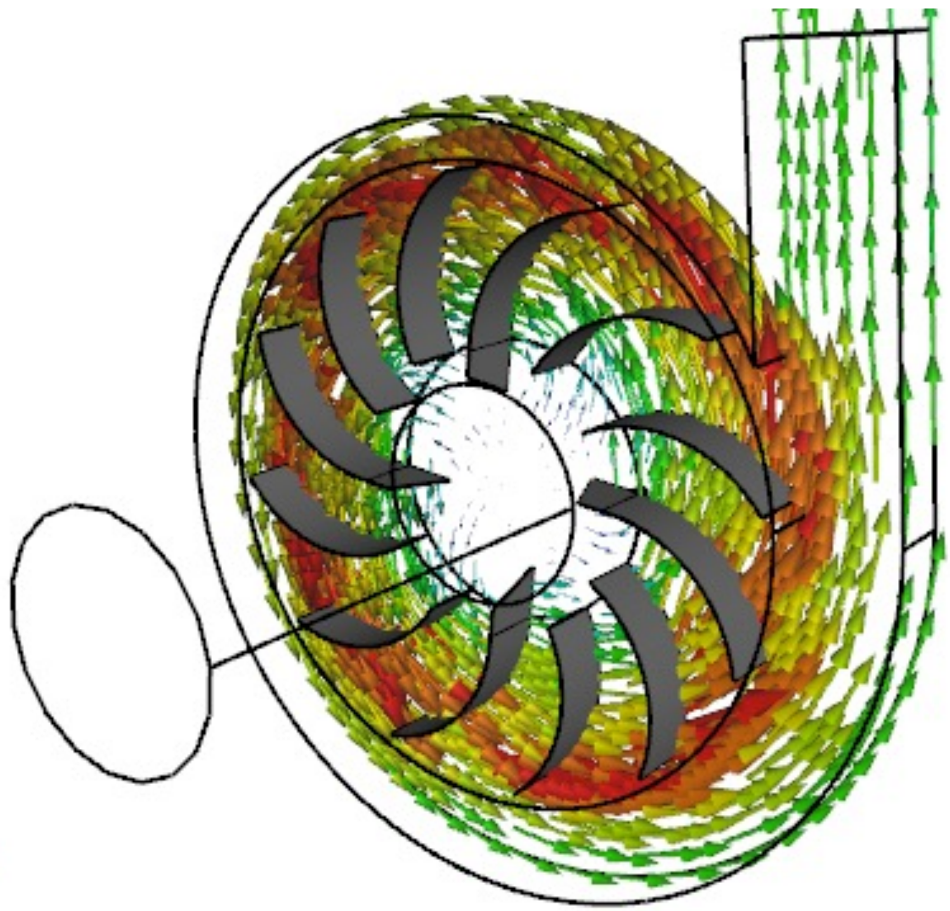
Centrifugal Blower

  - ❑ Air enters the impeller axially, passes through the impeller radially
  - ❑ The blades drag the air in a circular motion and centrifugal forces accelerate the airflow radially outward

http://www.leesii.com/axial-blower-vs-centrifugal-blower/

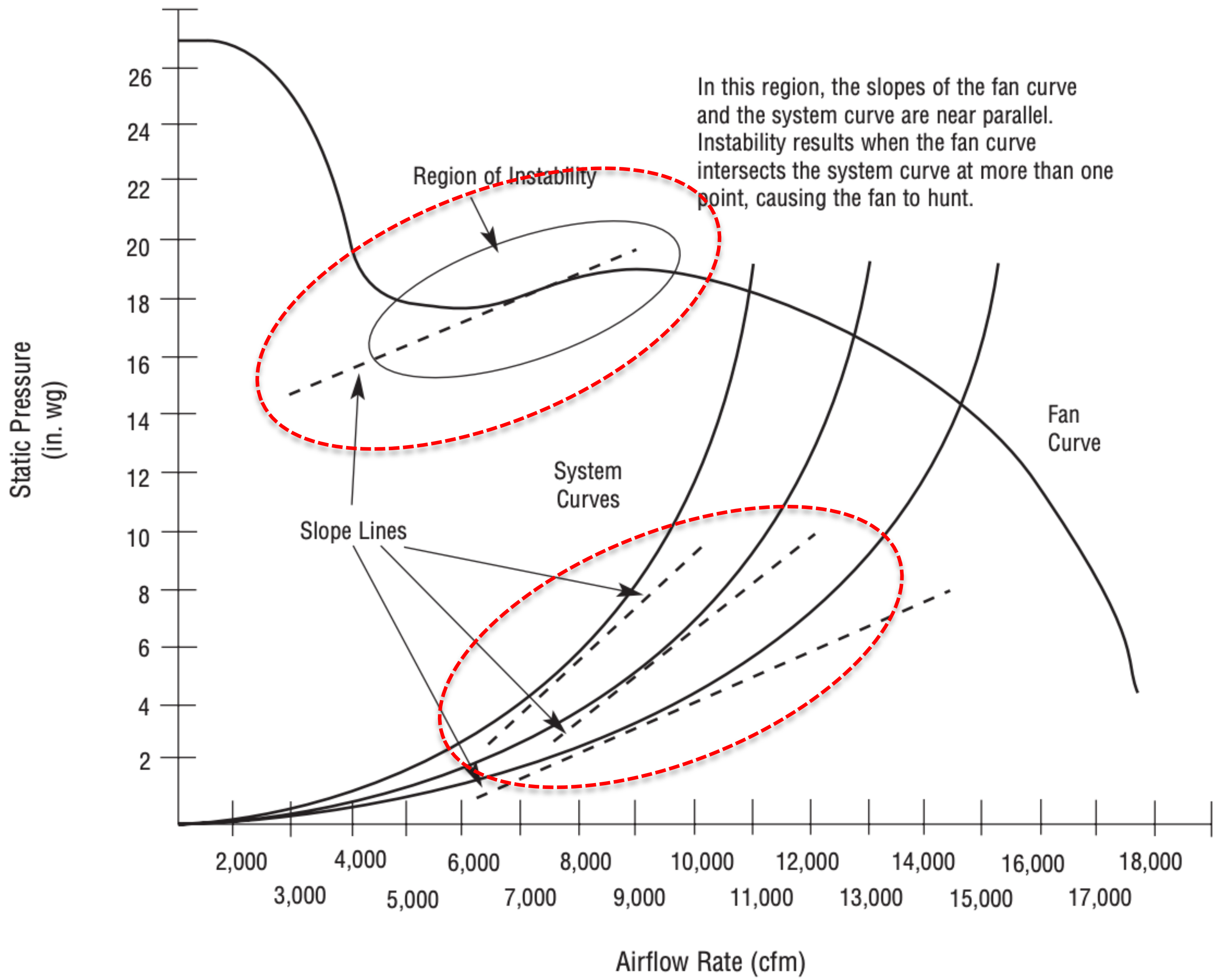
Centrifugal Fans

- Centrifugal fan flow patterns



https://www.symscape.com/blog/cfd-analysis-of-a-blower-for-a-small-dust-collector

Centrifugal Fans



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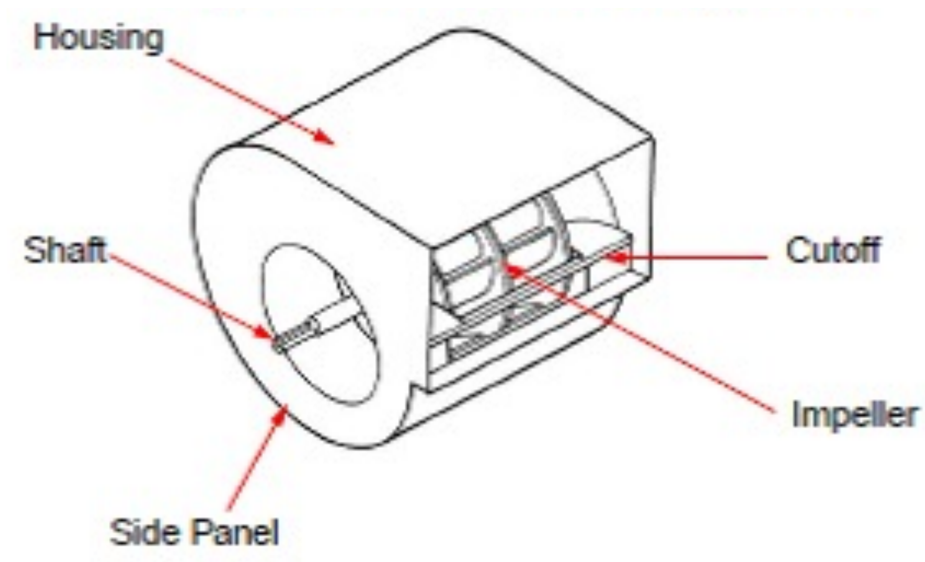
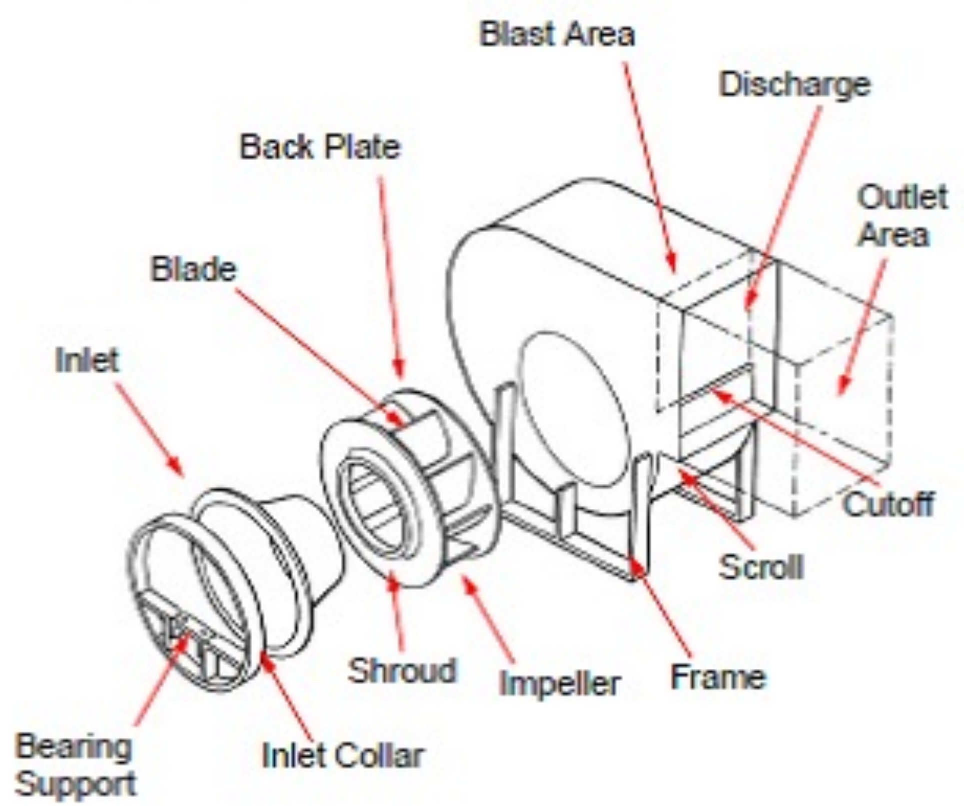
Centrifugal Fans

- Centrifugal fan terminology

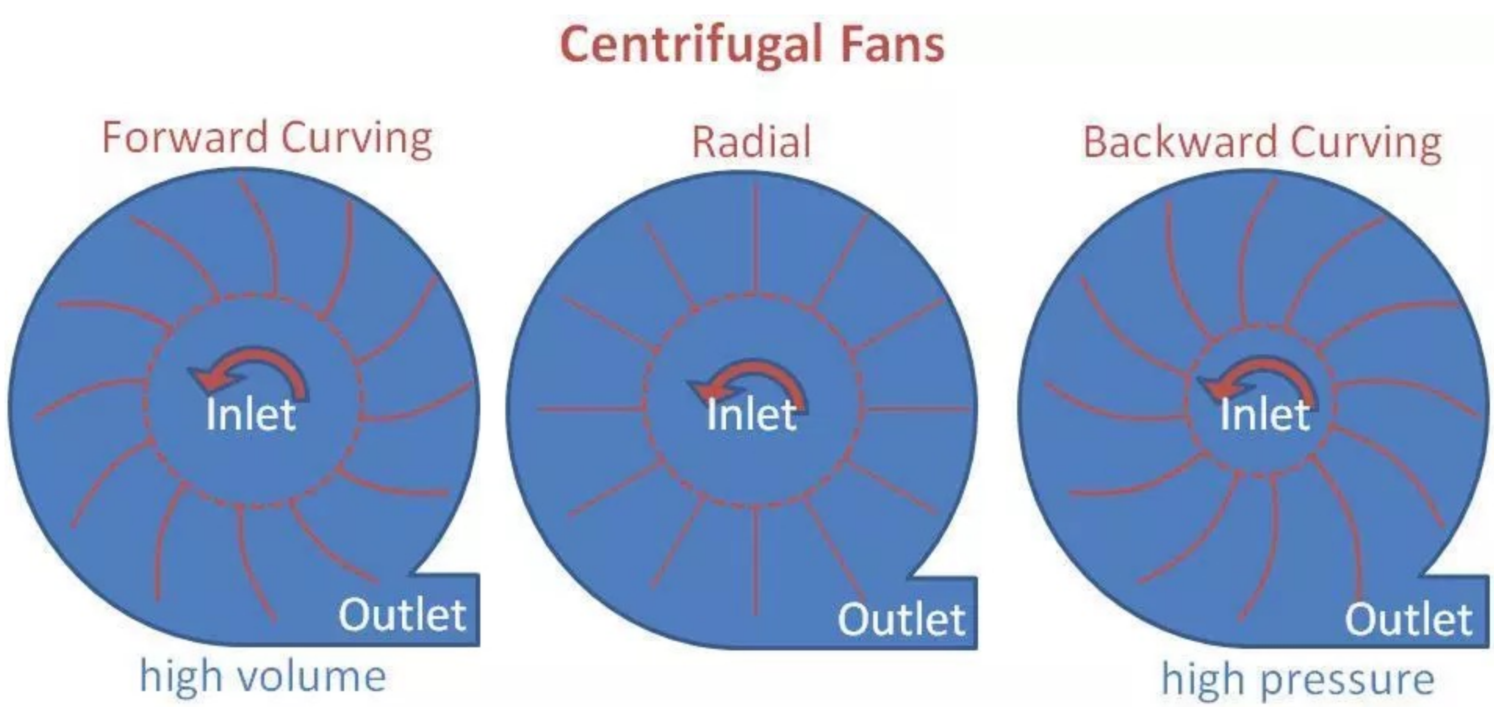




http://www.leesii.com/blog-post-with-right-sidebar/

Centrifugal Fans

- Centrifugal fans are categorized as:
  - ❑ Backward inclined
  - ❑ Radial
  - ❑ Forward curved



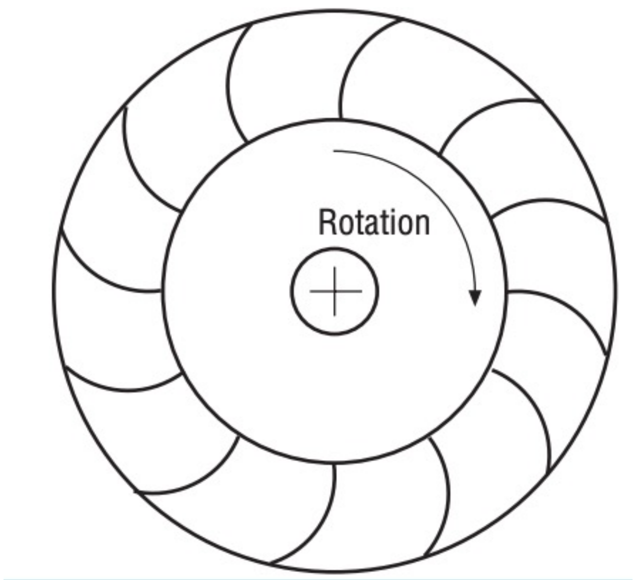
https://www.homeintheearth.com/tech_notes/earth-tubes/fans/

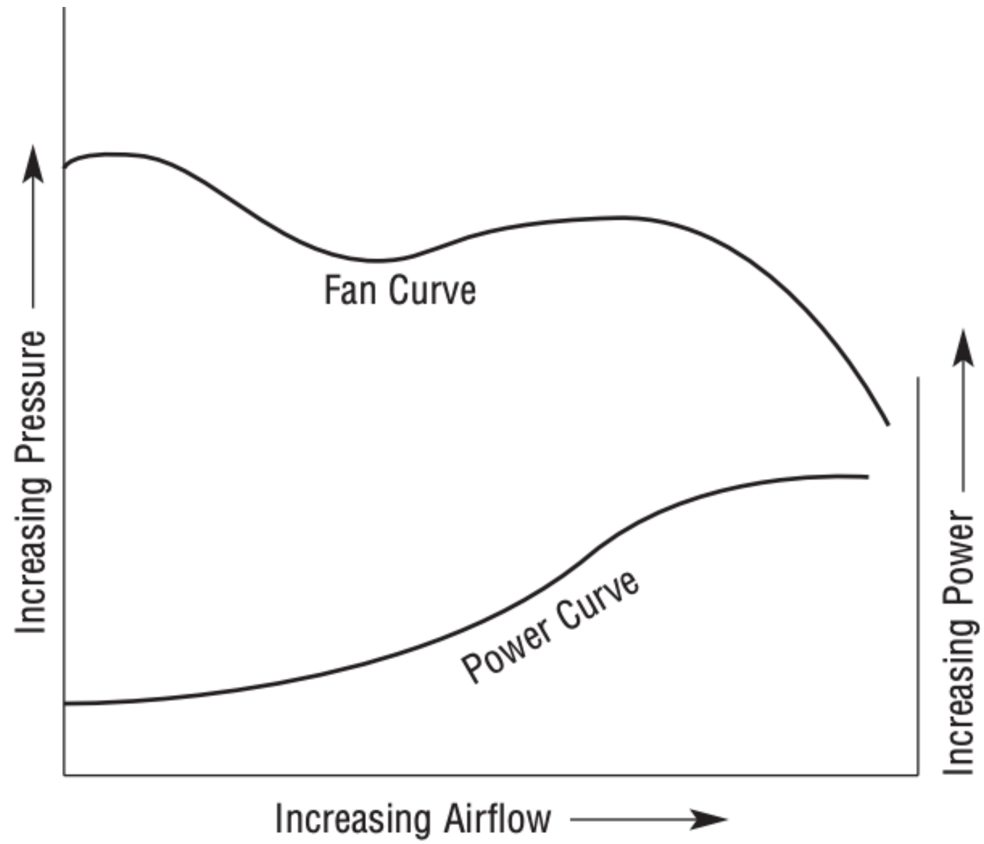
Centrifugal Fans

- One type of a centrifugal fans is ”Forward-curved blades” or forward centrifugal fans:
  - Low pressure applications
  - Lowest efficiency
  - Selection to be well to the right of the peak pressure point

Centrifugal Fans

- Forward centrifugal fans:





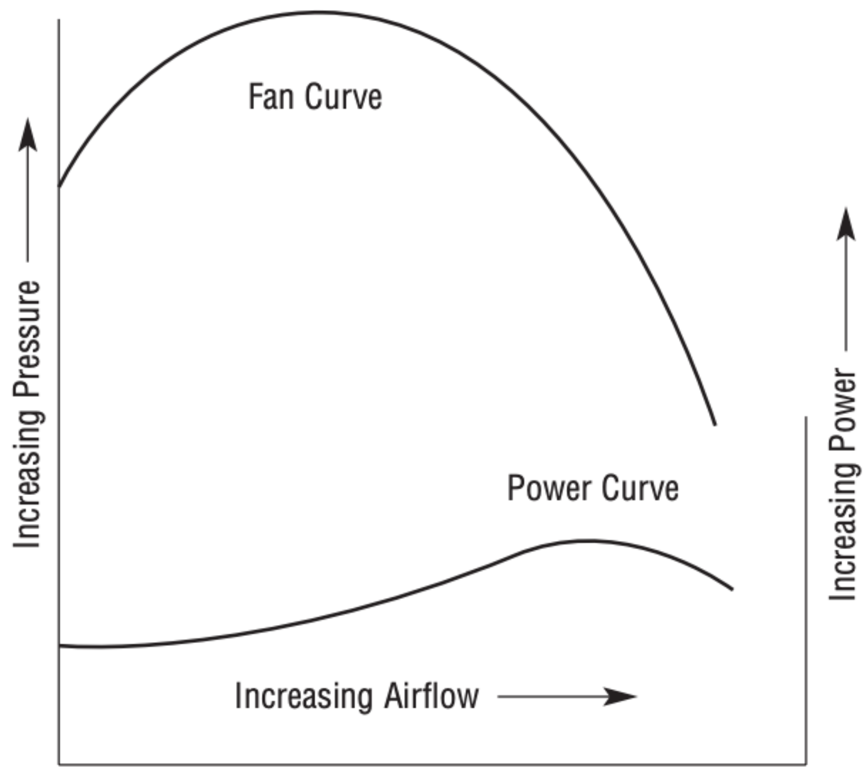
https://www.nrel.gov/docs/fy03osti/29166.pdf

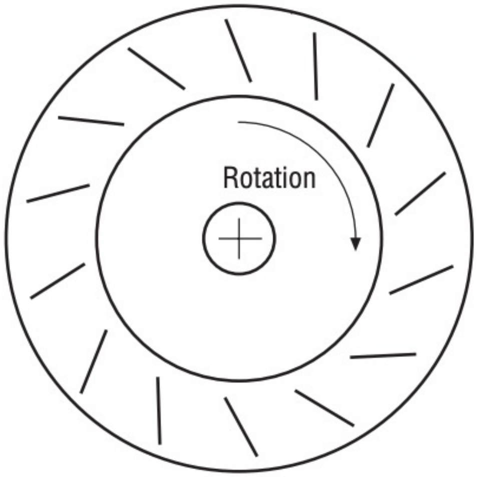
Centrifugal Fans

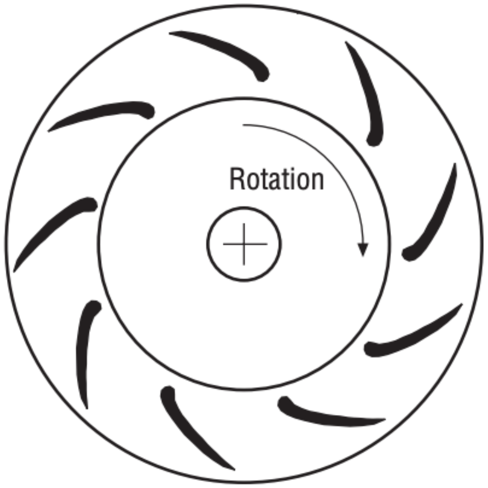
- "Backward-inclined" or "backward-inclined centrifugal airfoil" or "Backward centrifugal fans" are other types of centrifugal fans:
  - General HVAC system applications
  - Highest efficiency
  - Operate at highest speed
  - Load-limiting horsepower characteristics
  - Used in industrial applications

Centrifugal Fans

- Backward centrifugal fans:



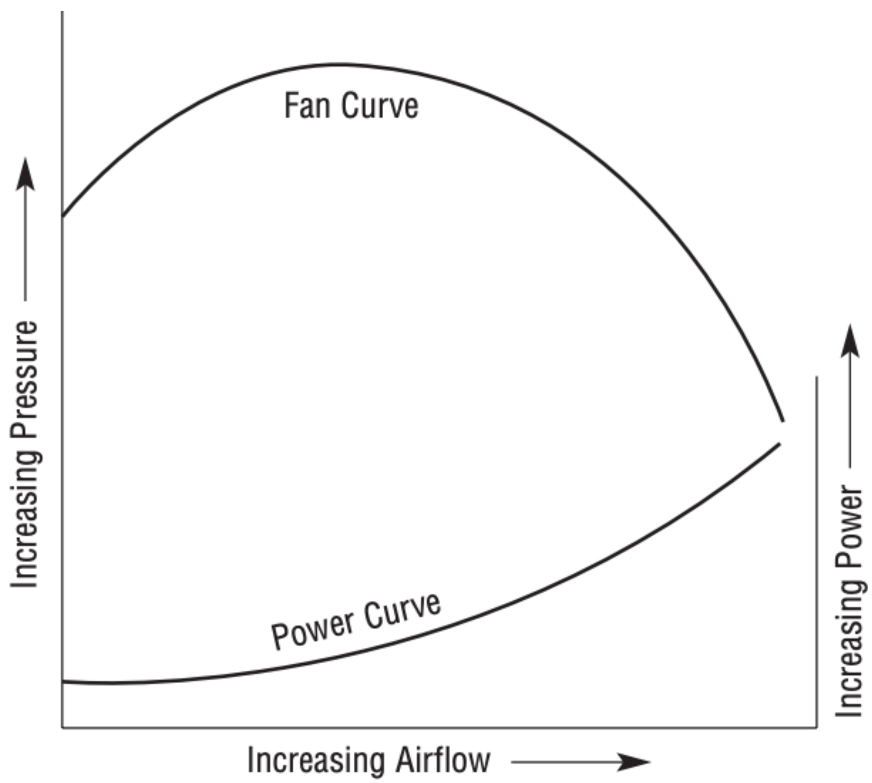


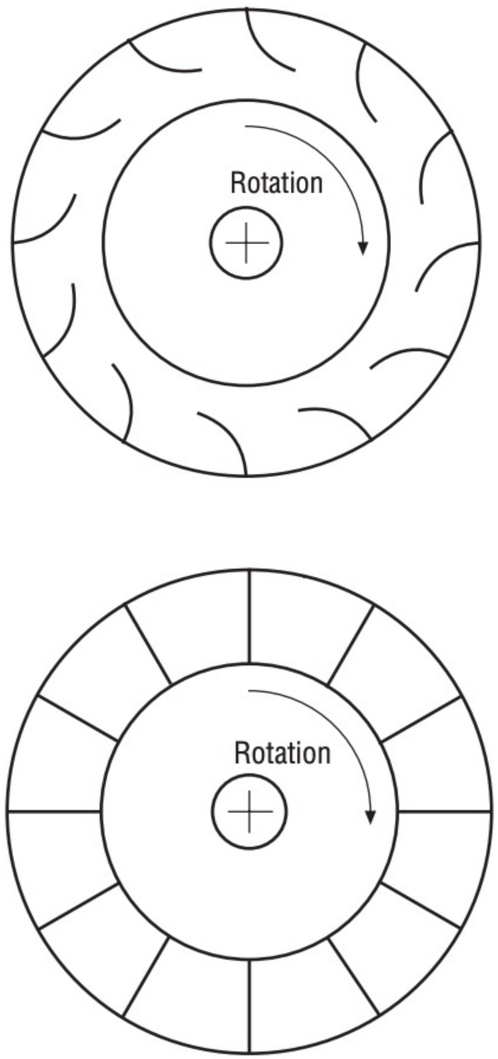


https://www.nrel.gov/docs/fy03osti/29166.pdf

Centrifugal Fans

- “Radial” and “Radial-tip” are other types of centrifugal fans:





https://www.nrel.gov/docs/fy03osti/29166.pdf

Centrifugal Fans

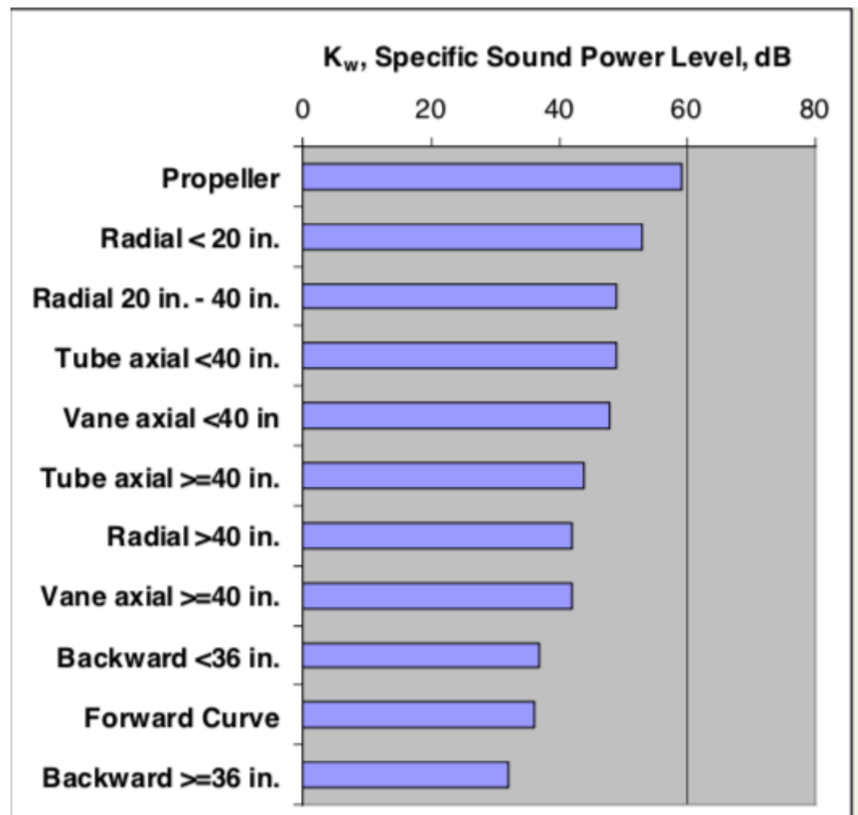
Item	Backward	Radial	Forward
Efficiency	High (80% to 86%)	Medium (50% to 77%)	Medium (50% to 70%)
Space required	High	Medium	Small
Speed for a given pressure rise	High	Medium	Low
Noise	Good	Fair	Poor
Number of blades	10 to 16	6 to 10	24 to 64
Horsepower	Limiting	Rising	Rising

CENTRIFUGAL FAN PERFORMANCE CURVES

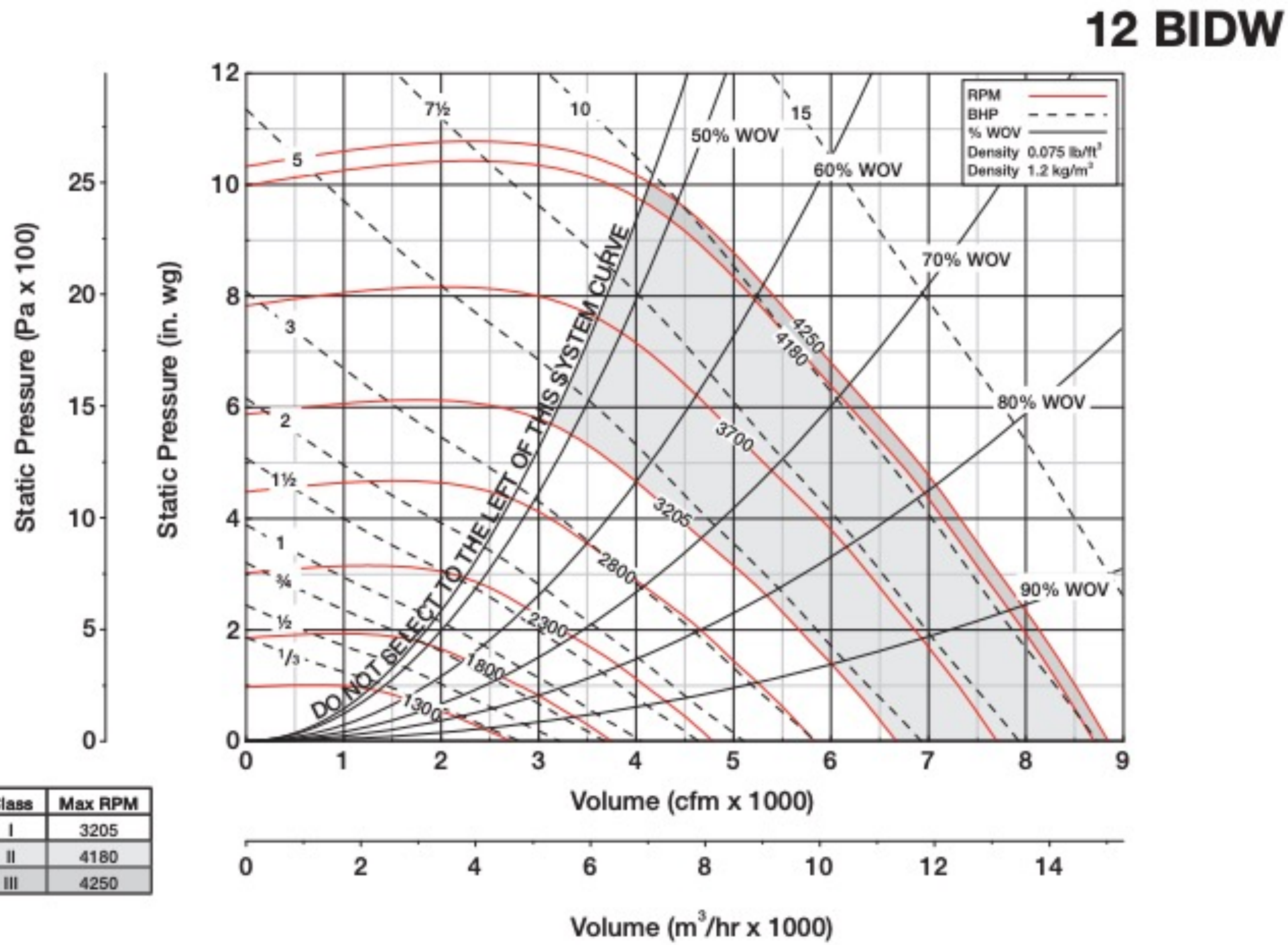
Centrifugal Fan Performance Curves

$$L_{w,f} = K_w + 10 \log Q_f + 20 \log P_t + C$$

- $L_{w,f}$: Fan sound power level (dB)
- K_w: Specific sound power level (dB)
- Q_f: Fan airflow rate (ft^3/min)
- P_t: Fan total pressure (in. w.c.)
- C: Fan efficiency correction



Centrifugal Fan Performance Curves



Class	Max RPM
I	3205
II	4180
III	4250

% WOV = (CFM X 100) / (RPM X 2.08)

https://content.greenheck.com/public/DAMProd/Original/10002/CentrifugalDWPerfSuppl_catalog.pdf

Centrifugal Fan Performance Curves

Sound Power [dB Ref 10^{-12} watts]

Inlet Sound Power, L_{Wi}

RPM	%WOV	1	2	3	4	5	6	7	8	$L_{Wi}A$
500	100	80	76	76	78	69	62	57	52	77
	80	78	74	73	75	67	60	55	51	74
	60	77	71	72	76	67	60	55	51	74
	50	77	70	72	76	67	60	55	51	75
	40	76	70	71	76	67	60	54	51	75
700	100	82	90	83	81	75	71	63	60	83
	80	81	88	80	77	71	66	58	53	79
	60	78	82	76	76	71	66	59	54	77
	50	77	79	75	75	71	66	59	54	76
	40	77	78	74	76	70	66	59	54	76
1000	100	87	94	92	90	86	82	75	70	91
	80	85	90	89	87	82	77	70	65	88
	60	84	86	85	84	80	76	70	66	85
	50	81	85	83	83	79	76	70	66	85
	40	81	85	83	83	79	76	71	67	85
1400	100	91	95	98	95	92	88	83	77	97
	80	89	92	96	93	90	85	79	75	95
	60	87	89	93	89	86	82	77	74	91
	50	87	89	91	88	85	82	78	75	90
	40	88	89	90	87	85	81	78	75	90
2000	100	99	101	105	106	99	96	92	88	106
	80	97	99	102	103	96	93	88	85	103
	60	93	95	99	99	94	91	87	85	100
	50	94	95	98	98	93	91	87	85	99
	40	96	97	99	98	93	91	89	87	100
2892	100	107	109	111	115	110	106	102	98	116
	80	105	107	108	112	107	103	98	95	113
	60	101	103	106	108	104	101	97	94	110
	50	103	103	107	107	103	100	97	94	109
	40	105	105	107	107	103	100	98	96	109

Outlet Sound Power, L_{Wo}

RPM	%WOV	1	2	3	4	5	6	7	8	$L_{Wo}A$
500	100	92	79	75	69	67	59	52	48	73
	80	92	78	72	65	64	54	48	46	71
	60	84	74	68	64	62	54	48	46	68
	50	83	73	68	64	63	54	49	46	67
	40	84	74	68	64	63	54	49	46	68
700	100	94	93	82	77	76	69	62	56	82
	80	91	90	80	73	70	63	56	52	79
	60	87	83	76	72	68	62	57	53	75
	50	86	81	74	71	68	62	57	54	74
	40	88	81	73	71	67	61	57	54	73
1000	100	100	95	91	87	86	81	74	67	90
	80	96	93	89	84	81	74	67	61	87
	60	92	89	84	79	78	72	66	62	83
	50	92	88	82	78	77	71	66	62	82
	40	92	88	81	77	76	71	67	63	81
1400	100	104	98	98	94	93	89	83	76	97
	80	101	96	96	92	91	86	80	72	95
	60	98	92	92	88	87	82	76	72	91
	50	98	93	91	87	85	81	76	72	90
	40	99	93	91	86	84	80	76	72	89
2000	100	110	106	108	110	102	98	94	88	109
	80	107	102	104	105	99	94	89	83	105
	60	103	98	98	100	96	91	86	81	101
	50	104	98	97	98	94	90	86	81	99
	40	107	101	96	96	93	89	86	82	98
2892	100	119	115	114	119	113	108	104	99	119
	80	116	112	110	115	110	104	100	94	115
	60	112	108	105	108	106	102	97	92	110
	50	113	109	105	106	104	100	96	92	109
	40	117	112	106	104	103	99	96	92	108

https://content.greenheck.com/public/DAMProd/Original/10002/CentrifugalDWPerfSuppl_catalog.pdf

Centrifugal Fan Performance Curves

24 BIDW
Wheel Diameter = 24½ in.
Outlet Area = 6.21 ft.^{2}
Tip Speed = 6.41 x RPM
Maximum BHP = (RPM/599)^3

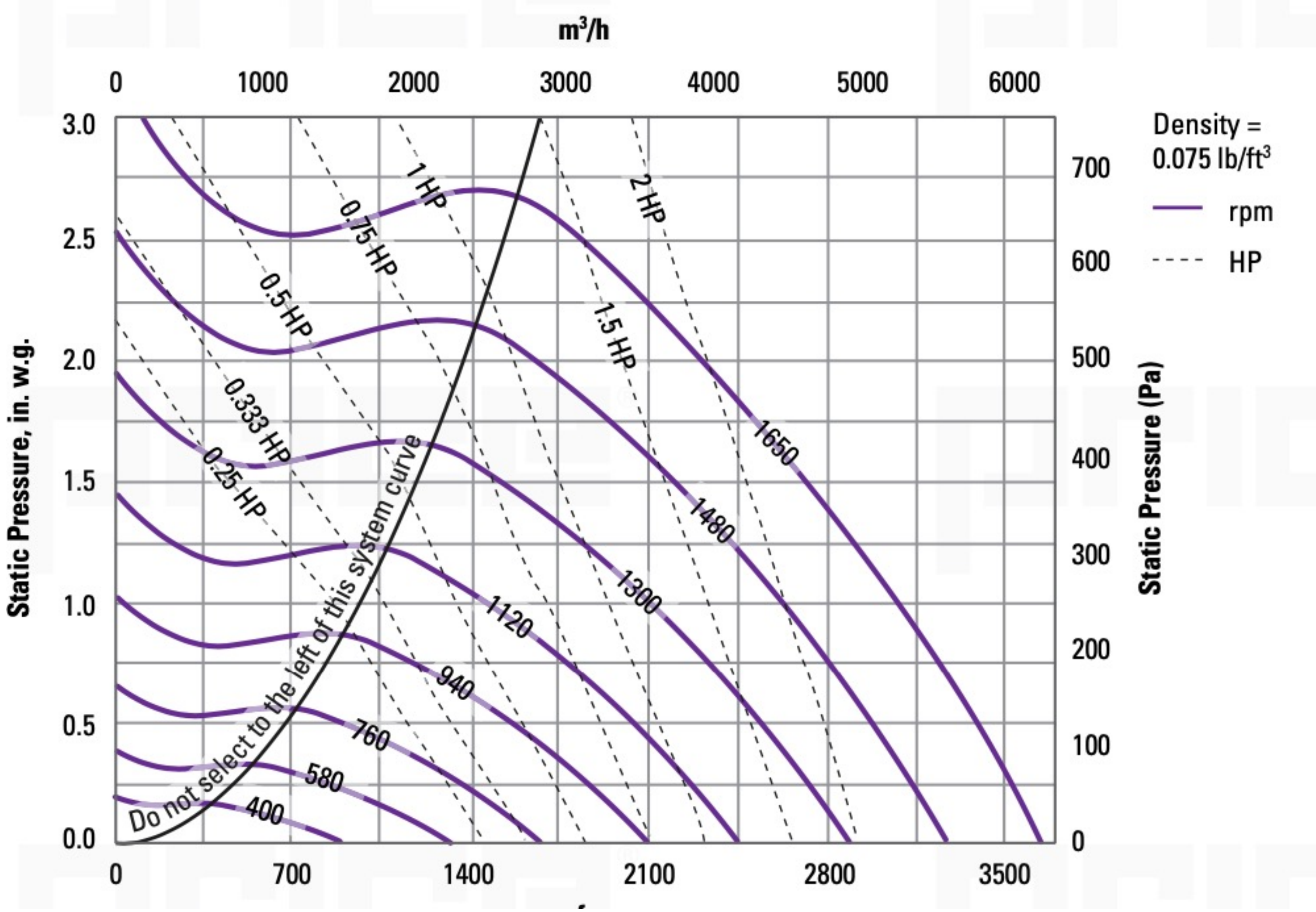
Minimum Starting HP = 1
Maximum RPM Class I = 1568
Maximum RPM Class II = 2045
Maximum RPM Class III = 2577

CFM	OV	STATIC PRESSURE (in. wg)																			
		0.25		0.50		0.75		1.00		1.25		1.50		1.75		2.00		2.25		2.50	
		RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP	RPM	BHP
5000	805	416	0.34	504	0.58	585	0.85	656	1.14												
6000	966	462	0.46	542	0.74	613	1.04	681	1.36	744	1.71	801	2.06								
7000	1127	512	0.62	586	0.94	650	1.26	711	1.62	769	1.99	826	2.39	878	2.79	927	3.20	972	3.63		
8000	1288	564	0.82	632	1.17	692	1.54	748	1.92	801	2.32	851	2.74	903	3.18	951	3.64	997	4.10	1040	4.57
9000	1449	619	1.07	679	1.46	737	1.87	789	2.28	838	2.70	886	3.16	931	3.62	977	4.11	1022	4.61	1065	5.11
10000	1610	675	1.36	730	1.79	783	2.23	833	2.70	879	3.15	923	3.62	968	4.12	1009	4.63	1049	5.16	1090	5.70
11000	1771	731	1.72	782	2.19	831	2.66	879	3.16	924	3.68	965	4.17	1005	4.68	1046	5.23	1085	5.78	1122	6.35
12000	1932	789	2.14	836	2.64	882	3.16	925	3.69	969	4.24	1009	4.80	1048	5.34	1084	5.88	1122	6.47	1159	7.08
13000	2093	848	2.63	891	3.17	933	3.73	975	4.29	1015	4.87	1055	5.47	1092	6.08	1128	6.66	1162	7.25	1196	7.86
14000	2254	907	3.20	947	3.76	986	4.37	1025	4.97	1063	5.58	1101	6.21	1137	6.86	1172	7.51	1205	8.14	1237	8.78
15000	2415	967	3.85	1003	4.44	1040	5.08	1077	5.73	1113	6.37	1148	7.03	1183	7.71	1217	8.41	1250	9.11	1281	9.79
16000	2576	1027	4.58	1060	5.21	1095	5.88	1129	6.57	1164	7.26	1198	7.95	1230	8.66	1264	9.39	1295	10.1	1326	10.9
17000	2737	1087	5.41	1118	6.07	1151	6.78	1184	7.50	1216	8.24	1248	8.97	1280	9.71	1310	10.5	1342	11.2	1372	12.0
18000	2898	1147	6.34	1177	7.04	1207	7.77	1239	8.53	1269	9.31	1300	10.1	1330	10.9	1359	11.6	1388	12.4	1418	13.3
19000	3059	1208	7.38	1236	8.11	1264	8.86	1294	9.67	1323	10.5	1352	11.3	1381	12.1	1410	12.9	1437	13.8	1465	14.6
20000	3220	1269	8.52	1295	9.29	1321	10.1	1350	10.9	1378	11.8	1405	12.6	1433	13.5	1460	14.3	1487	15.2	1513	16.1

https://content.greenheck.com/public/DAMProd/Original/10002/CentrifugalDWPerfSuppl_catalog.pdf

Centrifugal Fan Performance Curves

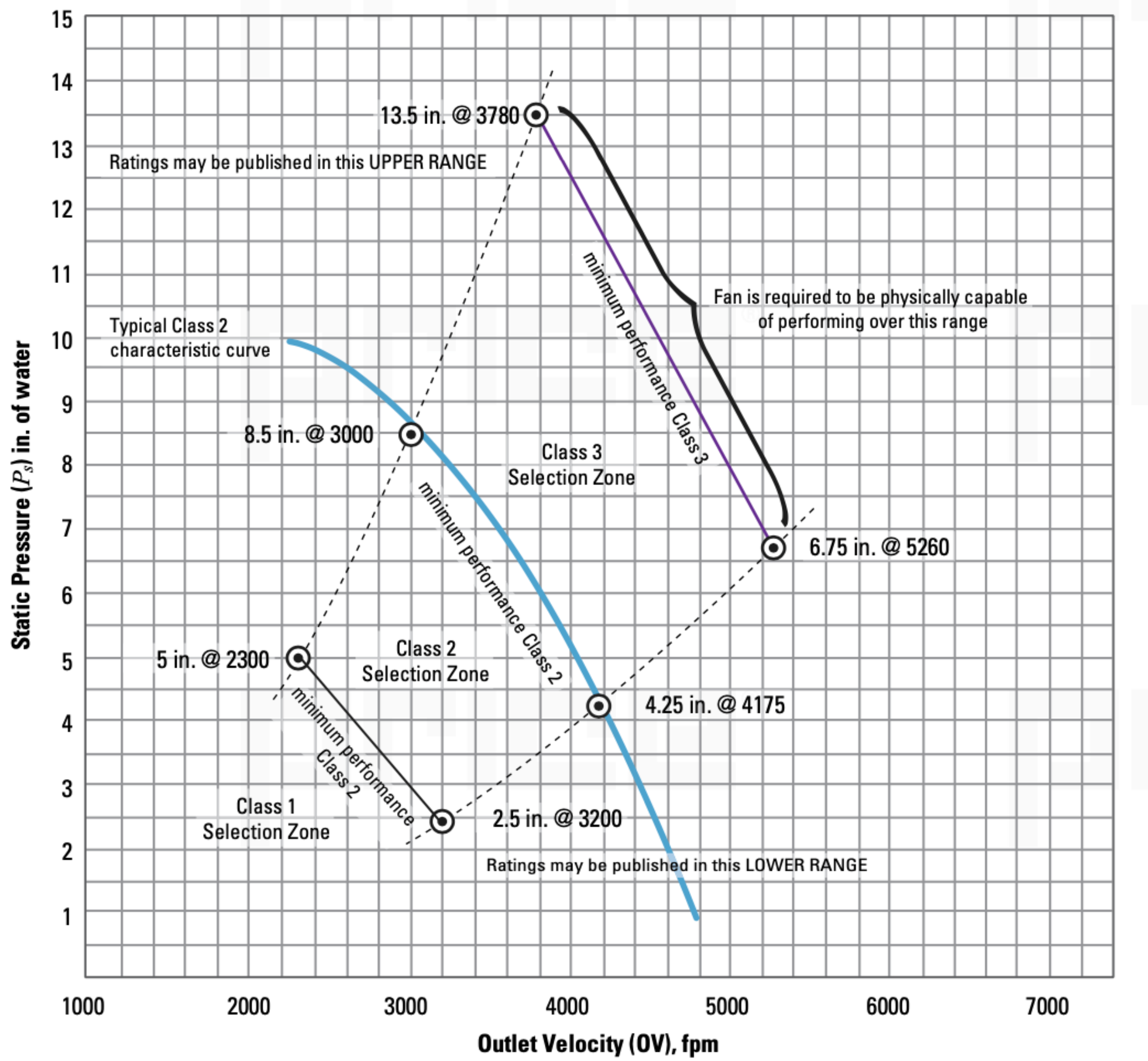
- Is this a forward or backward?



Price Industries Engineering Handbook

Centrifugal Fan Performance Curves

- Family fans usually specify their classes:

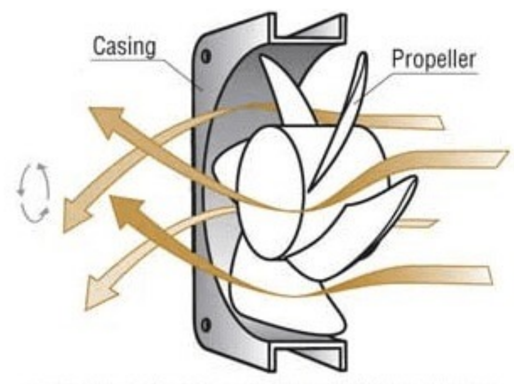


Price Industries Engineering Handbook

AXIAL FANS

Axial Fans

- Fans are categorized as:
  - ❑ Axial



Axial Blower

  - ❑ Flow is in an axial direction (Parallel to the shaft)
  - ❑ The flow is axial at entry and exit
  - ❑ Produce a pressure difference

http://www.leesii.com/axial-blower-vs-centrifugal-blower/

Axial Fans

- Axial fans are categorized as:
  - ❑ Tube
  - ❑ Vane
  - ❑ Propeller

Tube Axial	Vane Axial	Propeller
		

http://mechanicalgalaxy.blogspot.com/2015/03/types-of-axial-fans.html

FAN LAWS OR AFFINITY LAWS

Fan Laws

- Fan Laws ”or Affinity Laws”:
  - ❑ Fan capacity is directly ***proportional*** to the fan speed
  - ❑ Pressure (static, velocity or total) is proportional to the ***square*** of the fan Speed
  - ❑ Power required is proportional to the ***cube*** of the fan speed

Fan Laws

- Fan Laws ”or Affinity Laws”:
  - ❑ Q: Fan volume (cfm)
  - ❑ N: Rotational speed (rpm)
  - ❑ P: Total pressure (in. w.c.)
  - ❑ W: Brake Horsepower
  - ❑ ρ: Fan density (lb/ft^3)

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} . \frac{\rho_1}{\rho_2}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^2 . \frac{\rho_1}{\rho_2}$$

$$\frac{W_1}{W_2} = \left(\frac{N_1}{N_2}\right)^3 . \frac{\rho_1}{\rho_2}$$

Fan Laws

- Fan Laws ”or Affinity Laws”:

Flow Rate Reduction	Fan Energy Savings
10%	27%
20%	47%
30%	66%
40%	78%
50%	87%

Flow Rate Increase	Increased Fan Energy
10%	33%
20%	73%
30%	120%
40%	174%
50%	237%

FAN POWER (HORSEPOWER)

Fan Power (Horsepower)

- Theoretical air power:
  - Use the first Law of Thermodynamics
  - Cancel the terms to reach to this equation:

$$W_f = \dot{m}\frac{(p_i - p_o)}{\rho}$$

Fan Power (Horsepower)

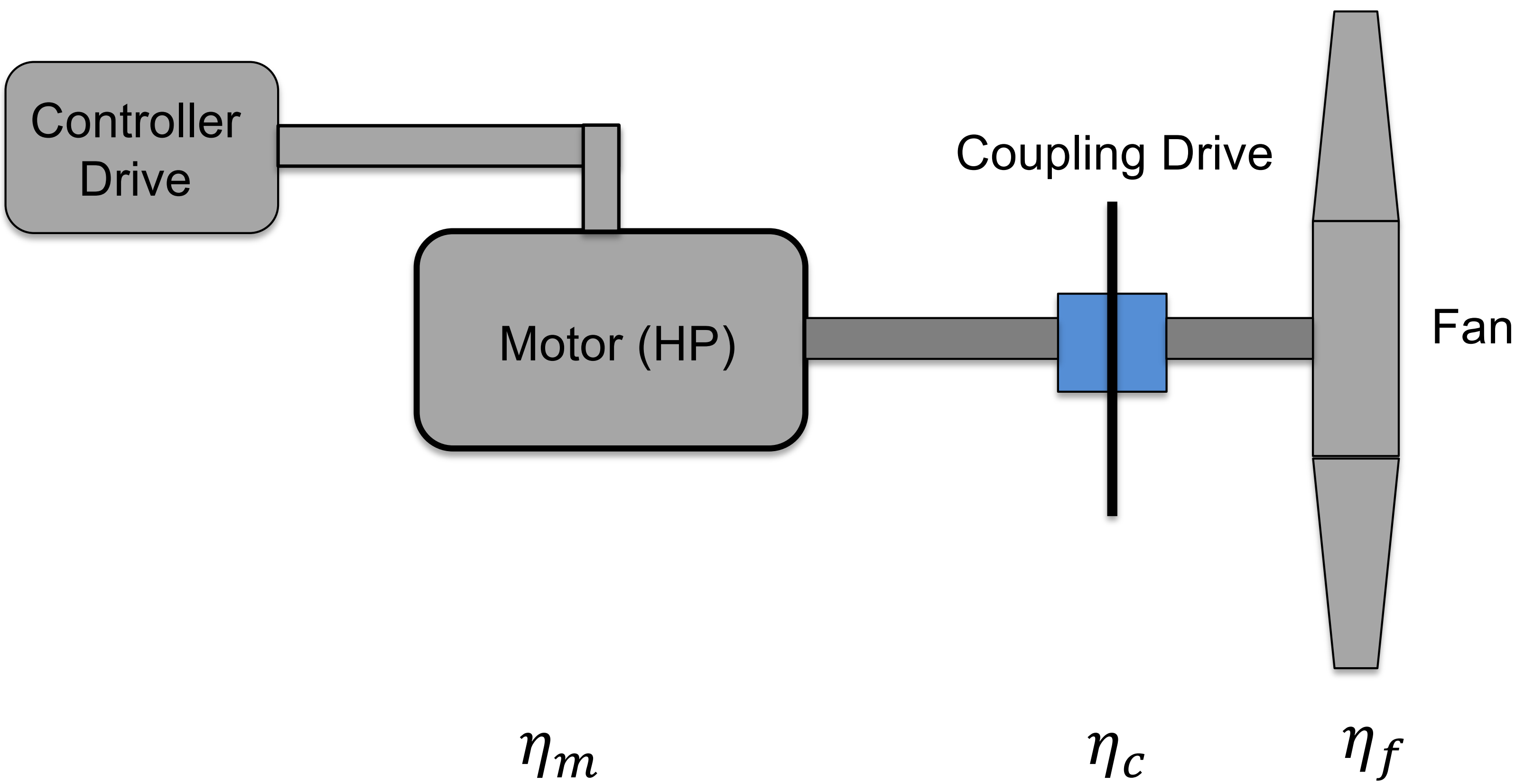
- Theoretical air power is equal to:

$$W_t = \frac{Q_s \times \Delta p_t}{6{,}356}$$

- ❑ Q_s: is in CFM
- ❑ Δp_t: is the pressure drop in “in w.c.”
- ❑ W_t: is in HP

Fan Power (Horsepower)

- The fan power is impacted by different inefficiencies:
  - ❑ η_f: Fan total efficiency
  - ❑ η_c: Coupling efficiency (1-drive losses)
  - ❑ η_m: Motor efficiency



Fan Power (Horsepower)

- Consider the losses, the fan efficiency is:

$$\eta_f = \frac{W_t}{W_{shaft}}$$

$$\eta_f = \frac{Q_s \times \Delta P_t}{6{,}356 \times W_{shaft}}$$

Fan Power (Horsepower)

- The total fan power is defined as:

$$W_t = \frac{Q_s \times \Delta P_t}{6{,}356 \times \eta_f \times \eta_c \times \eta_m}$$

Fan Power (Horsepower)

- ASHRAE 90.1-2019 Appendix G recommends: Each HVAC system at fan system design conditions shall not exceed the allowable fan system motor nameplate horsepower (Option 1) or fan system bhp (Option 2) as shown in Table 6.5.3.1-1

Table 6.5.3.1-1 Fan Power Limitation[a]

	Limit	Constant Volume	Variable Volume
Option 1: Fan *system* motor nameplate hp	Allowable *motor nameplate hp*	$hp \leq cfm_S \times 0.0011$	$hp \leq cfm_S \times 0.0015$
Option 2: Fan *system* bhp	Allowable fan *system* bhp	$bhp \leq cfm_S \times 0.00094 + A$	$bhp \leq cfm_S \times 0.0013 + A$

a. where
cfm_S=maximum design supply airflow rate to *conditioned spaces* served by the *system* in cubic feet per minute
hp=maximum combined motor *nameplate horsepower*
bhp= maximum combined fan-brake horsepower
A =sum of ($PD \times cfm_D/4131$)
where
PD=each applicable pressure drop adjustment from Table 6.5.3.1-2 in in. of water
cfm_D=the design airflow through each applicable device from Table 6.5.3.1-2 in cubic feet per minute

CLASS ACTIVITY

Class Activity

- Example: A fan delivers 8,000 cfm of air at 70 F and 29.92 in. Hg (density is 0.0750 lb_m/ft^3) against a static pressure of 2.0 in. w.c. when speed is 600 rpm and the power input is 5.0 bhp

- Find: If the inlet air temperature is raised to 200 F (density is 0.0602 lb_m/ft^3) but fan speed stays the same. What are the new static pressure and horsepower?

Class Activity

- Solution:

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^2 \left(\frac{\rho_1}{\rho_2}\right)$$

$$P_2 = (1)^2 \left(\frac{\rho_2}{\rho_1}\right) = (2.0)\left(\frac{0.0602}{0.0750}\right) = 1.6\ in.w.c.$$

Class Activity

- Solution:

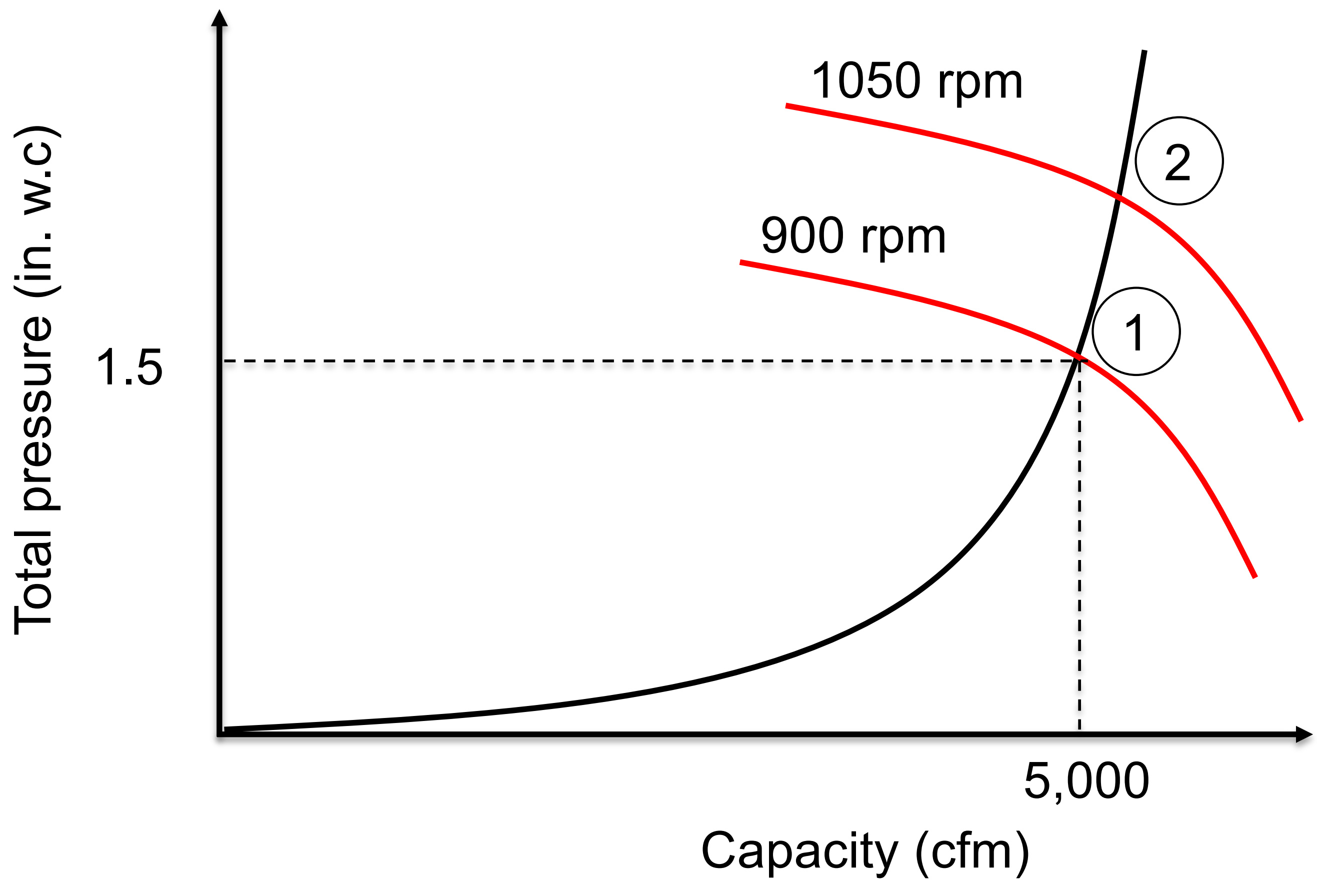
$$\frac{W_1}{W_2} = \left(\frac{N_1}{N_2}\right)^2 \left(\frac{\rho_1}{\rho_2}\right)$$

$$W_2 = W_1 \left(\frac{\rho_2}{\rho_1}\right) = (5)\left(\frac{0.0602}{0.0750}\right) = 4.0\ bhp$$

CLASS ACTIVITY

Class Activity

- **Example:** Estimate the capacity, total pressure, power requirement when the speed is increased to 1,050 rpm. The initial power requirement is 2 hp.



Class Activity

- Fan Laws ”or Affinity Laws”:

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} . \frac{\rho_1}{\rho_2}$$

$$Q_2 = Q_1 \frac{N_3}{N_1} = (5{,}000)\left(\frac{1{,}050}{900}\right) = 5{,}833 \ \frac{ft^3}{min}$$

Class Activity

- Fan Laws ”or Affinity Laws”:

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^2 \cdot \frac{\rho_1}{\rho_2}$$

$$P_2 = P_1 \left(\frac{N_2}{N_1}\right)^2 = (1.5)\left(\frac{1{,}050}{900}\right)^2 = 2.04\ in.w.c.$$

Class Activity

- Fan Laws ”or Affinity Laws”:

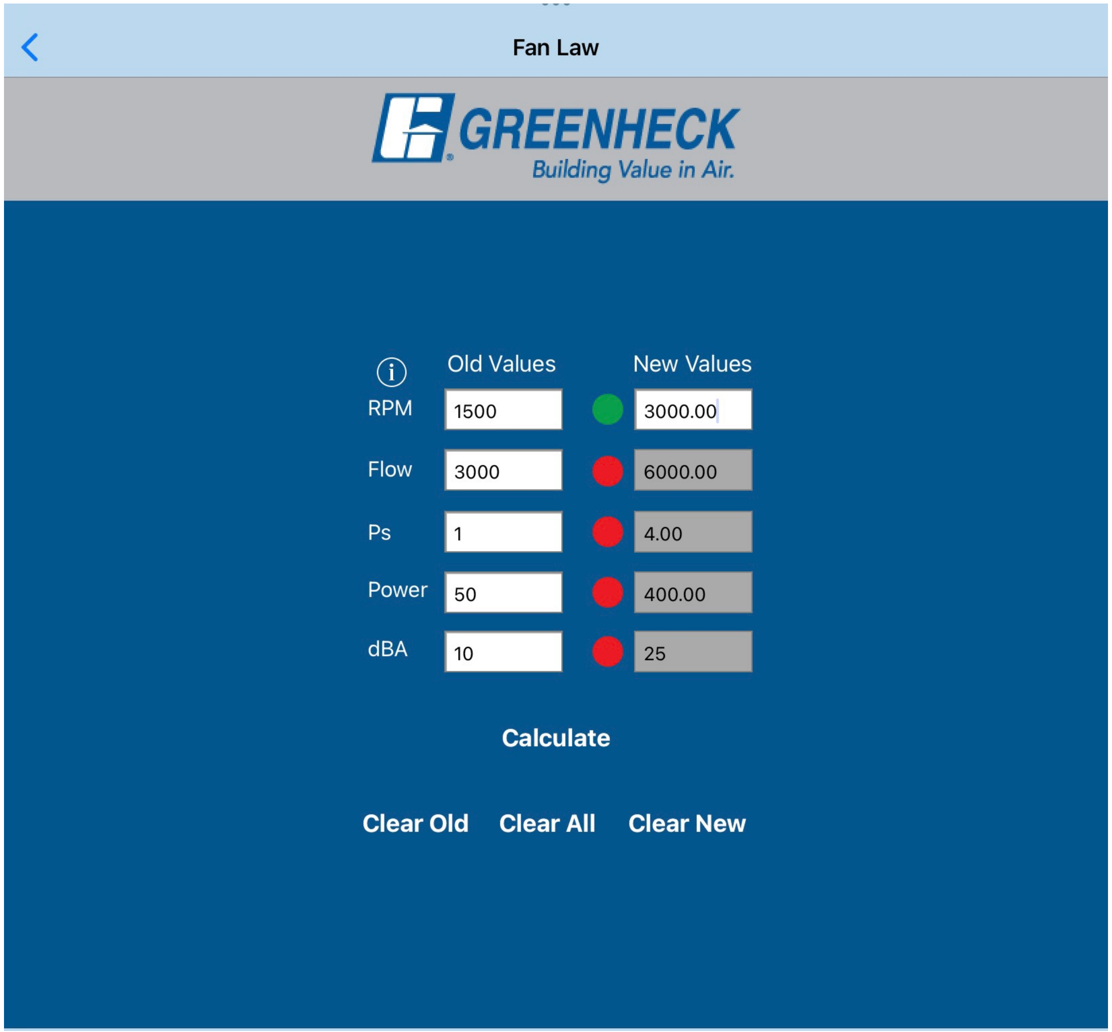
$$\frac{W_1}{W_2} = \left(\frac{N_1}{N_2}\right)^3 \cdot \frac{\rho_1}{\rho_2}$$

$$W_2 = W_1 \left(\frac{N_2}{N_1}\right)^3 = 2\left(\frac{1{,}050}{900}\right)^3 = 3.2\ hp$$

APP (FAN LAW)

App (Fan Law)

- We can also use the GreenHeck App

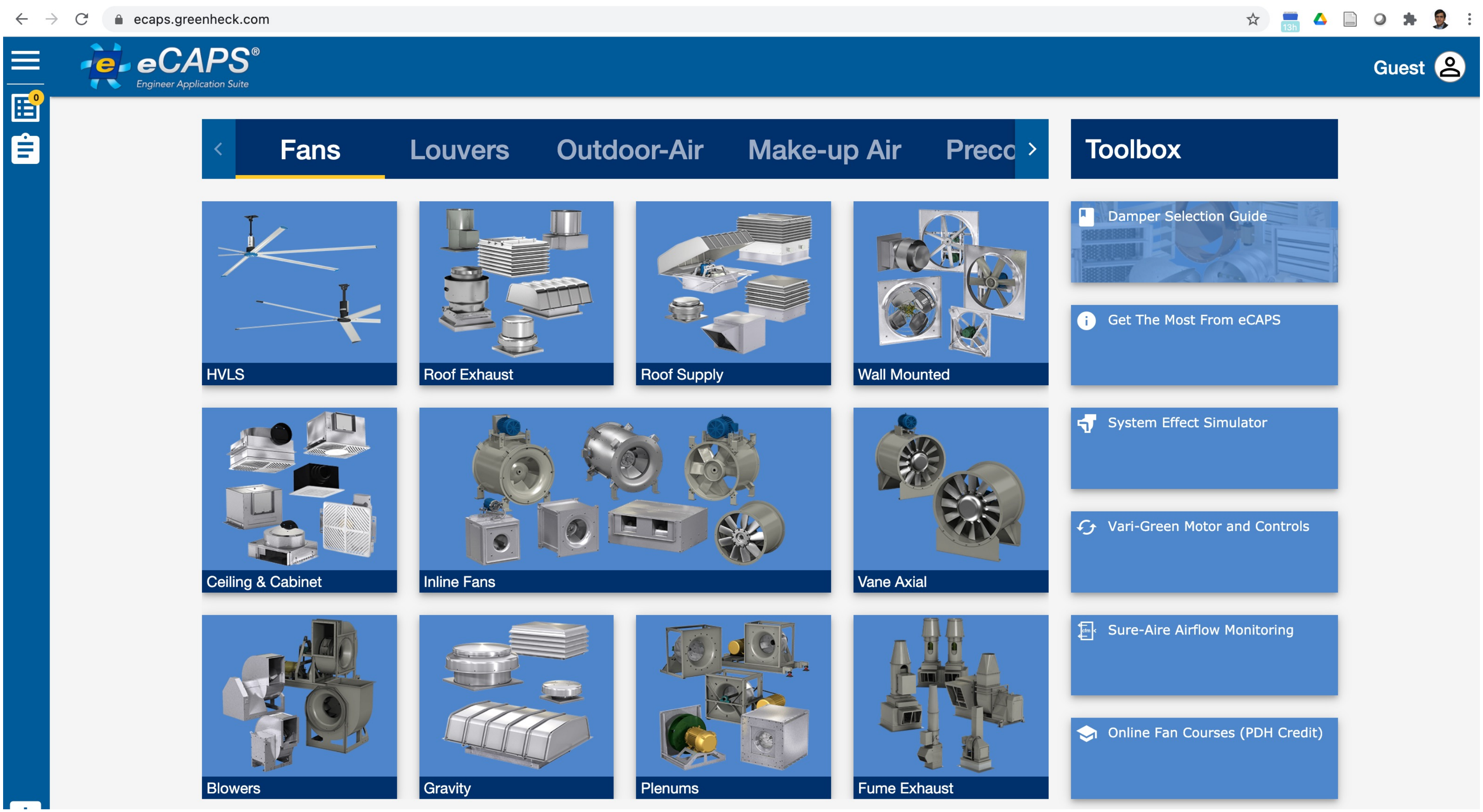


Try to calculate the examples using equations and the app!

SOFTWARE TOOLS

Software Tools

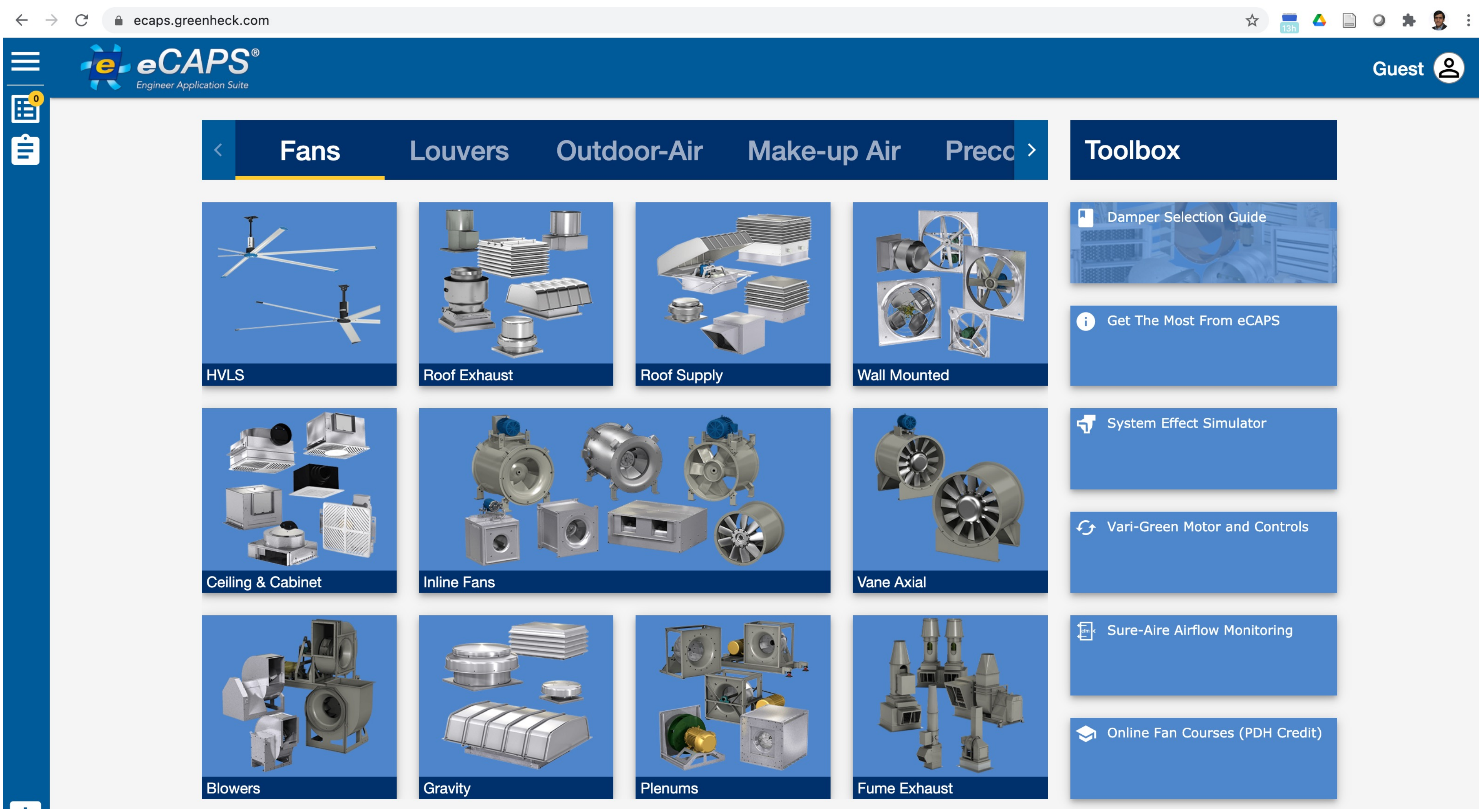
- Greenheck has a good sizing tool:



https://ecaps.greenheck.com/

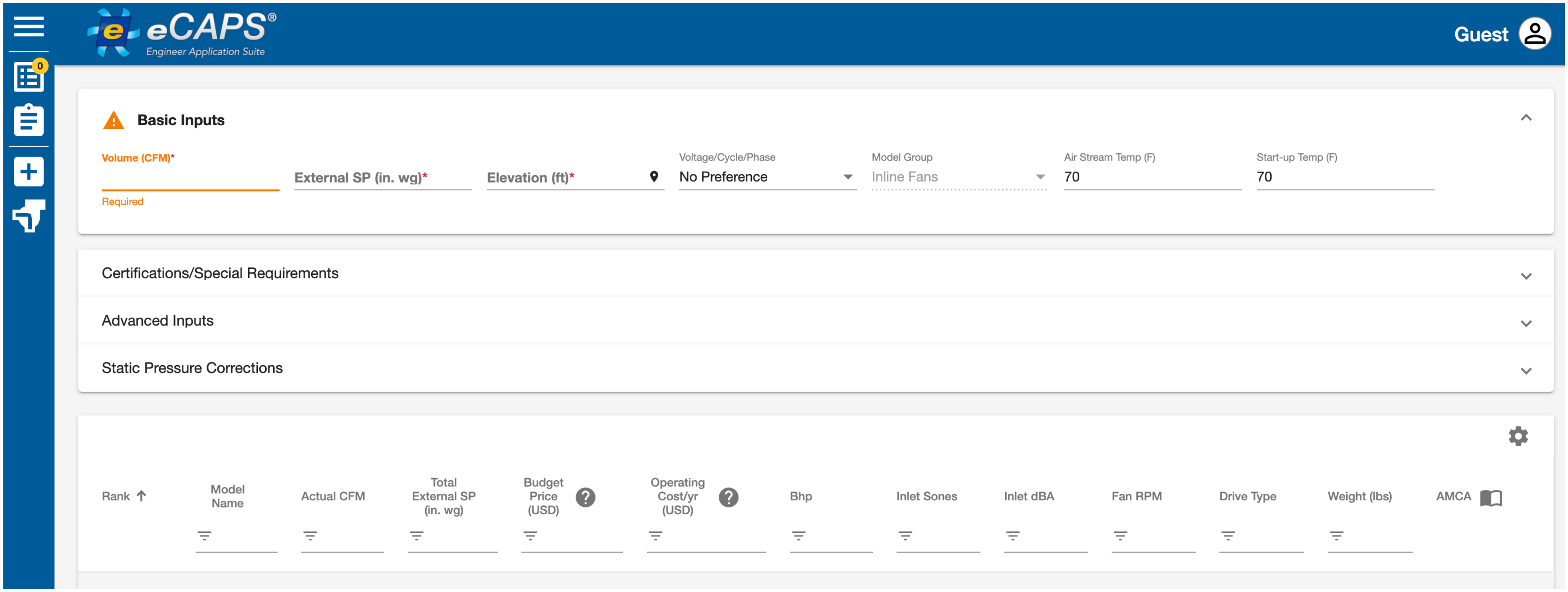
Software Tools

- Select “Inline Fans”



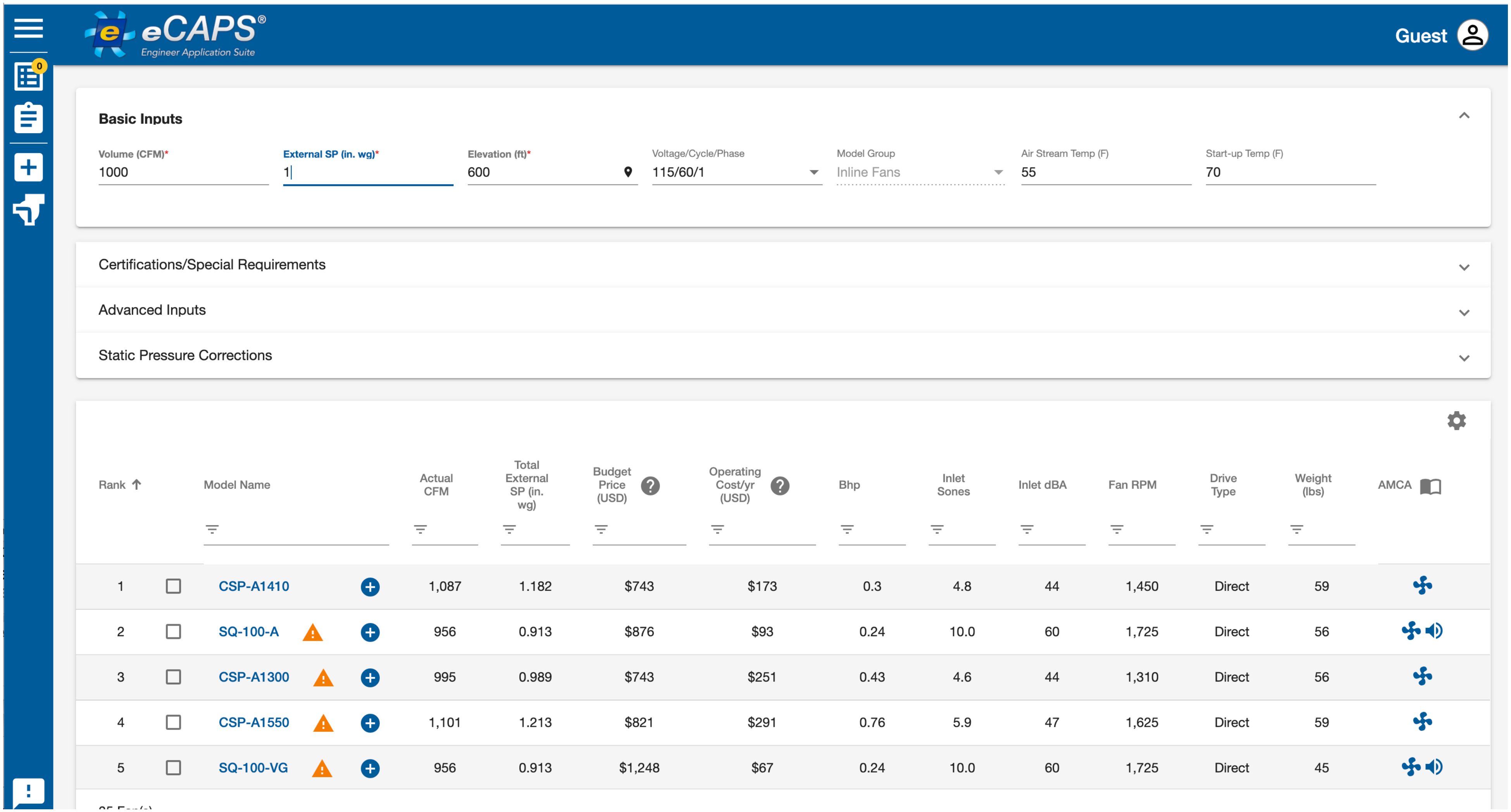
Software Tools

- Select “Inline Fans”



Software Tools

- Start filling the “CFM”, “SP”, “Elevation”, …



Software Tools

- Click on a model, and look at the specs: