2016 Annual Conference

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Seminar 13

Advances in Compressor Design, Testing, and Performance Modeling for New Efficiency Standards and Alternate Refrigerants

Representation of a Positive Displacement Compressor Map with Vapor Injection

St. Louis, Missouri

Learning Objectives

1. Describe how the new, low-GWP alternative refrigerants affect the compressor design, performance characteristics and operation.

2. Explain the purpose of compressor rating standards.

3. Describe the proper use of compressor performance maps.

4. Derive from compressor performance maps the actual compressor performance at real operating conditions in the system.

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Acknowledgments

- Ingersoll Rand and Jay Johnson, Compressor Group manager, for giving permission to present test results.

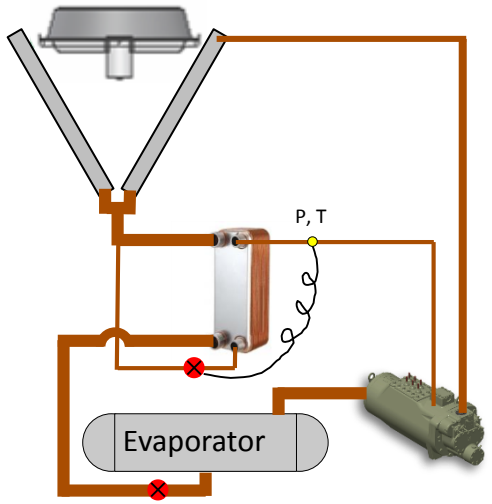
- Gordy Powell for presenting at the ASHRAE Summer Meetings.

Outline/Agenda

- Introduction to vapor injection
- Standards around compressor maps
- Analysis of 10-coefficient format
- Vapor injection equation format
- Analysis of proposed format.

Vapor Injection

- PD Compressor vapor injection is commonly used in HVAC.
  - Cycle efficiency enhancement
  - Capacity increase
  - Compression cooling
- Economizer applications are popular in chilled water systems.
- BPHE is one method of lowering the entering evaporator temperature.



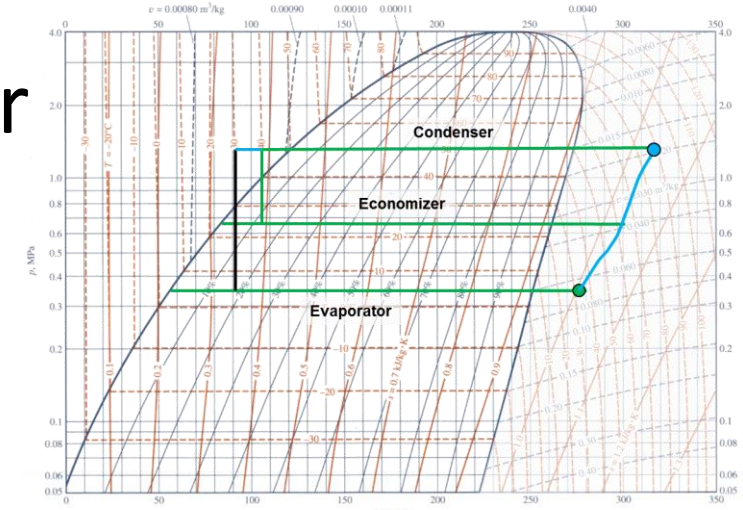


Chart A-11 R134a *ph* diagram. (*Source:* Based on *Thermodynamic Properties of HFC-134a (1,1,1, 2-tetrafluoroethane)*, DuPont Company, Wilmington, Delaware, 1993, with permission.)

Vapor Injection

- Port opens to the pocket early in compression.
- Port closes with the pocket at an elevated pressure.
- Port flow is a new variable requiring characterization.
- Port flow is dependent on the upstream injection pressure.

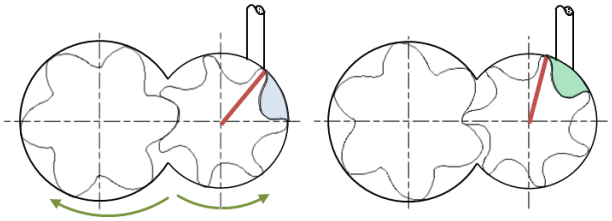
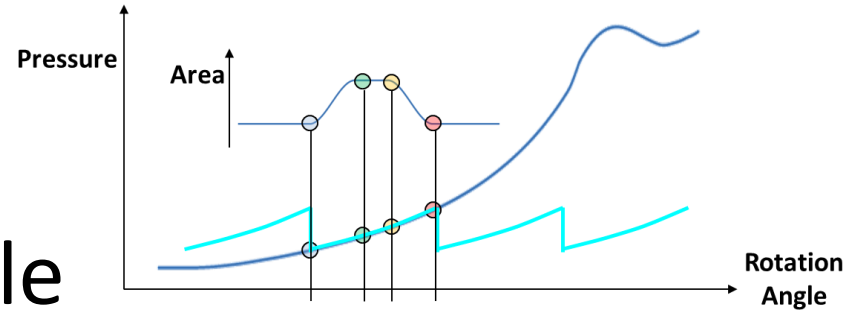


Fig. 1 Fig. 2



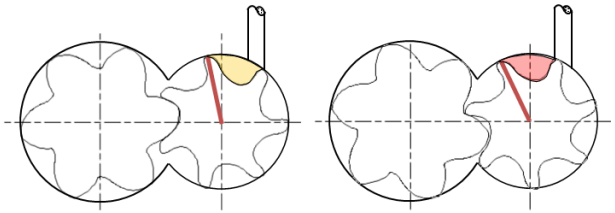
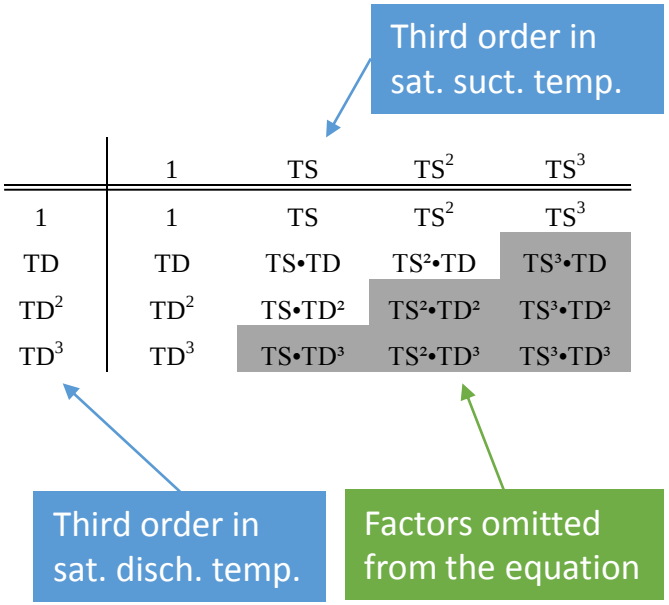


Fig. 3 Fig. 4

Performance Rating Standard

- AHRI standard 540 covers positive displacement compressors.
- Compressor performance is represented by a 10-coefficient equation.
- No reference to the derivation of this equation format
- Currently no provisions in the standard for vapor injection.

AHRI 10-Coefficient Model



10-Coefficient Curve Fit

- 20 point data set was curve fit using the AHRI 540 format.
- A linear regression was performed on the coefficients.
- Results showed the statistically significant coefficients.
  - 7 out of 10 for power
  - 5 out of 10 for mass flow

- P-value shows significance.
- Low is better
- Value of 0.05 is a 95% confidence interval.

Power

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.356527	99.99%	99.99%	99.87%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	49.5	14.8	3.34	0.008	
S	0.801	0.186	4.30	0.002	1481.74
D	-0.247	0.389	-0.63	0.540	12378.97
S2	0.01628	0.00303	5.38	0.000	1080.55
SD	-0.01316	0.00370	-3.56	0.005	11673.72
D2	0.00506	0.00339	1.49	0.166	57767.07
S3	0.000062	0.000024	2.56	0.029	188.42
DS2	-0.000129	0.000028	-4.61	0.001	1818.75
SD2	0.000075	0.000019	4.00	0.003	6735.65
D3	0.000001	0.000010	0.13	0.900	17887.48

Regression Equation

kW = 49.5 + 0.801 S - 0.247 D + 0.01628 S2 - 0.01316 SD + 0.00506 D2 + 0.000062 S3
- 0.000129 DS2 + 0.000075 SD2 + 0.000001 D3

Mass Flow

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.560449	100.00%	100.00%	99.99%

Coefficients

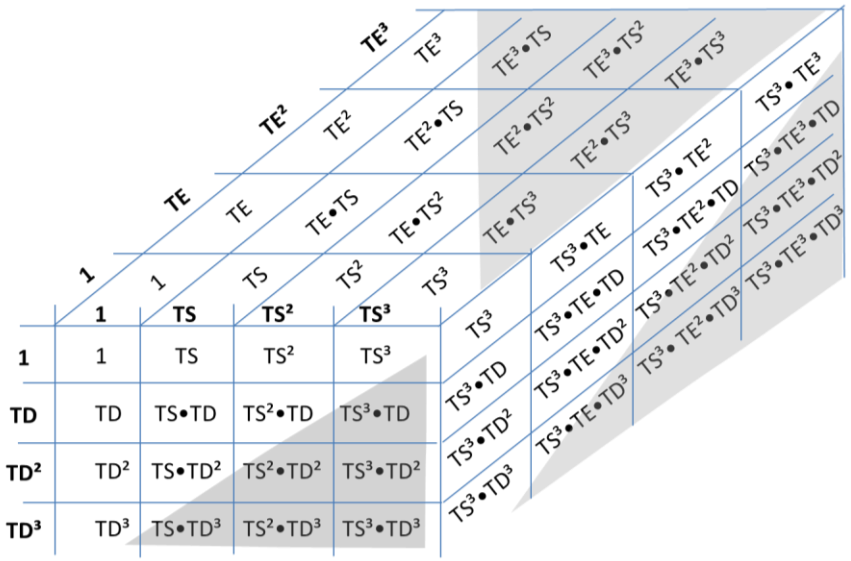
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	205.9	23.3	8.83	0.000	
S	3.366	0.293	11.50	0.000	1481.74
D	-1.055	0.612	-1.71	0.115	12378.97
S2	0.03672	0.00476	7.71	0.000	1080.55
SD	0.00746	0.00581	1.28	0.228	11673.72
D2	0.00989	0.00533	1.86	0.093	57767.07
S3	0.000104	0.000038	2.70	0.022	188.42
DS2	-0.000027	0.000044	-0.61	0.557	1818.75
SD2	-0.000035	0.000030	-1.19	0.261	6735.65
D3	-0.000039	0.000015	-2.54	0.029	17887.48

Regression Equation

Mass Flow = 205.9 + 3.366 S - 1.055 D + 0.03672 S2 + 0.00746 SD + 0.00989 D2 + 0.000104 S3
- 0.000027 DS2 - 0.000035 SD2 - 0.000039 D3

Model with Injection

- With vapor injection saturated economizer temperature is another independent variable.
- Using the 10-coefficient logic a 23-coefficient model was created.



23-Coefficient Curve Fit

- Power – 11 of 23 coefficients have a > 95% probability of significance.
- Mass Flow – 9 of 23 coefficients have > 95% probability of significance.
- Econ Flow – 5 of 23 coefficients have a >95% probability of significance

Power

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.227901	100.00%	99.99%	99.99%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	55.7	11.3	4.95	0.000	
S	-2.049	0.569	-3.60	0.001	133449.15
D	-0.955	0.211	-4.53	0.000	35623.73
S2	0.0040	0.0166	0.24	0.813	315069.78
SD	0.03334	0.00741	4.50	0.000	453498.22
D2	0.01044	0.00155	6.75	0.000	117611.39
S3	-0.000069	0.000053	-1.29	0.202	8689.29
DS2	-0.000145	0.000130	-1.11	0.268	377849.30
SD2	-0.000142	0.000043	-3.26	0.002	349646.53
D3	-0.000005	0.000004	-1.37	0.177	28411.97
E	0.906	0.481	1.89	0.064	126138.64
E2	-0.01223	0.00935	-1.31	0.196	932973.26
SE	0.0170	0.0217	0.78	0.438	1893150.39
ED	0.00196	0.00466	0.42	0.676	397927.94
E3	-0.000041	0.000078	-0.52	0.604	807976.63
SE2	0.000528	0.000244	2.16	0.035	2365562.69
ES2	-0.000026	0.000237	-0.11	0.913	617500.18
DE2	0.000134	0.000076	1.77	0.083	1507631.20
ED2	-0.000061	0.000030	-2.07	0.043	516433.18
SED	-0.000566	0.000175	-3.23	0.002	2515464.22
EDS2	0.000001	0.000001	0.86	0.395	441168.96
SED2	0.000003	0.000000	7.60	0.000	381602.46
SDE2	-0.000004	0.000001	-2.90	0.005	1337005.51

Mass Flow

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.579269	100.00%	100.00%	99.99%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	200.7	28.6	7.02	0.000	
S	5.30	1.45	3.67	0.001	133449.15
D	-0.595	0.536	-1.11	0.272	35623.73
S2	0.0792	0.0423	1.87	0.066	315069.78
SD	0.0152	0.0188	0.81	0.423	453498.22
D2	0.01280	0.00393	3.26	0.002	117611.39
S3	0.000469	0.000136	3.46	0.001	8689.29
DS2	0.000231	0.000329	0.70	0.486	377849.30
SD2	0.000163	0.000110	1.48	0.145	349646.53
D3	-0.000029	0.000010	-2.87	0.006	28411.97
E	-0.77	1.22	-0.63	0.532	126138.64
E2	0.0453	0.0238	1.90	0.062	932973.26
SE	-0.1031	0.0552	-1.87	0.067	1893150.39
ED	-0.0284	0.0118	-2.40	0.020	397927.94
E3	-0.000738	0.000198	-3.73	0.000	807976.63
SE2	0.001927	0.000620	3.11	0.003	2365562.69
ES2	-0.001434	0.000602	-2.38	0.021	617500.18
DE2	0.000632	0.000192	3.29	0.002	1507631.20
ED2	-0.000159	0.000075	-2.12	0.039	516433.18
SED	-0.000771	0.000446	-1.73	0.089	2515464.22
EDS2	0.000001	0.000004	0.38	0.703	441168.96
SED2	-0.000000	0.000001	-0.22	0.824	381602.46
SDE2	-0.000002	0.000003	-0.53	0.596	1337005.51

Econ Flow

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.856495	99.89%	99.85%	99.73%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-148.9	42.3	-3.52	0.001	
S	-6.24	2.14	-2.92	0.005	133449.15
D	-0.052	0.793	-0.07	0.947	35623.73
S2	-0.0088	0.0626	-0.14	0.888	315069.78
SD	0.0117	0.0278	0.42	0.676	453498.22
D2	-0.00121	0.00581	-0.21	0.835	117611.39
S3	-0.000764	0.000200	-3.81	0.000	8689.29
DS2	-0.000904	0.000487	-1.86	0.069	377849.30
SD2	-0.000286	0.000163	-1.76	0.085	349646.53
D3	-0.000004	0.000015	-0.24	0.813	28411.97
E	6.82	1.81	3.77	0.000	126138.64
E2	-0.0808	0.0352	-2.30	0.025	932973.26
SE	0.0511	0.0817	0.63	0.534	1893150.39
ED	0.0004	0.0175	0.03	0.980	397927.94
E3	0.000519	0.000292	1.77	0.081	807976.63
SE2	-0.000277	0.000916	-0.30	0.763	2365562.69
ES2	0.000146	0.000891	0.16	0.870	617500.18
DE2	-0.000161	0.000284	-0.57	0.573	1507631.20
ED2	0.000069	0.000111	0.62	0.538	516433.18
SED	0.001208	0.000659	1.83	0.072	2515464.22
EDS2	0.000010	0.000005	1.88	0.065	441168.96
SED2	0.000001	0.000002	0.64	0.527	381602.46
SDE2	-0.000009	0.000005	-1.79	0.078	1337005.51

Reducing Coefficients

- Factors with a low probability of correlation can be removed from the equation.
- This exercise was performed on coefficients 11-23.
- If a factor was not significant for two or more variables it was removed.
- This exercise reduced the number of coefficients to 12

		P-Values		
Coeff #	Term	kW	Mass Flow	Econ Flow
2	S	0.000	0.000	0.000
3	D	0.506	0.019	0.631
4	S^2	0.000	0.000	0.123
5	SD	0.000	0.032	0.725
6	D^2	0.032	0.008	0.535
7	S^3	0.005	0.000	0.027
8	DS^2	0.000	0.303	0.002
9	SD^2	0.000	0.318	0.180
10	D^3	0.777	0.000	0.400
11	E	0.000	0.000	0.000
12	SED	0.000	0.000	0.000
	R-sqrd	99.9%	100%	99.5%

Conclusions

- AHRI 540 is not sufficient for compressor with vapor injection.
- Injection flow is a new dependent variable requiring characterization.
- Injection saturation temperature is a new independent variable requiring specification.
- A 23-coefficient equation format has been presented in the spirit of the AHRI 540 10-coefficient format.
- A single data set was used to show that there is potential to reduce the number of coefficients to 12.

Bibliography

- ANSI/AHRI Standard 540. 2015. Standard for performance rating of positive displacement refrigerant compressors and compressor units.

- Aute V., Martin C., Radermacher R. 2015. AHRI Project 8013: A study of methods to represent compressor performance data over an operating envelope based on a finite set of test data

Questions?

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