Inverter Drive Control and Seasonal Performance Analysis of a Single Speed Unitary Air-Source Split-System Heat Pump

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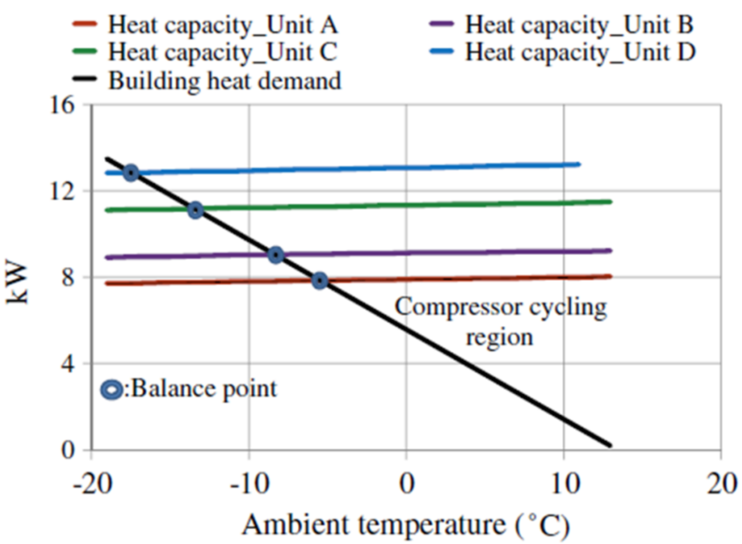
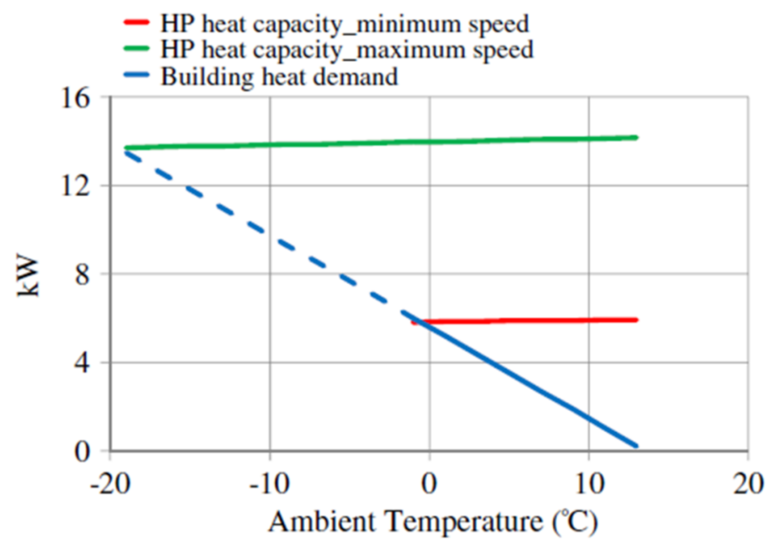
Research Goals

- To demonstrate the use of a new inverter drive technology designed specifically to be used with existing single speed technology.
- To improve the seasonal performance of an air source heat pump by enabling the variable speed operation of compressor and fans.

Why Variable Speed?

- The benefits of variable speed systems have been well documented and these systems are widely available in the market
  - Improved efficiency, comfort, and control
- Variable capacity systems offer seasonal performance advantages due to their ability to closely match part loads and reduce cycling.



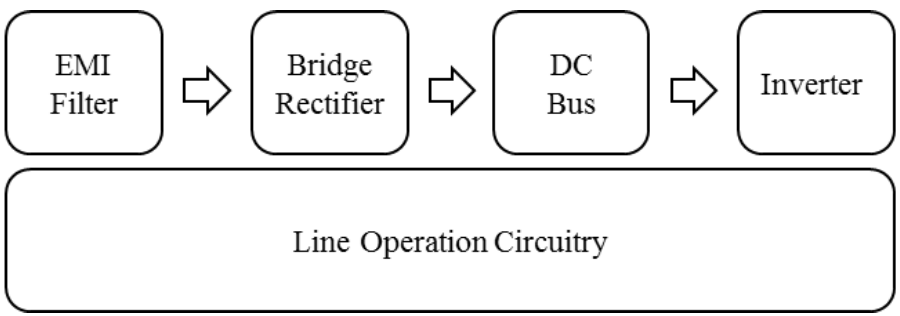


Building demands and heat capacities of single-speed and variable-speed heat pump
[Madani et al. 2011]

The Inverter Drive

- The inverter drive is a new variable speed drive designed to be used in a traditional single speed heat pump having a single speed compressor and fans.
  - The drive enables variable speed operation of single speed components
- How it works:
  - The drive is connected in line between a power source and a single speed heat pump
  - The inverter drive system operates directly from the line at high power.
  - The drive is enabled at part load conditions to allow variable speed operation.

Block diagram of a typical variable speed drive.

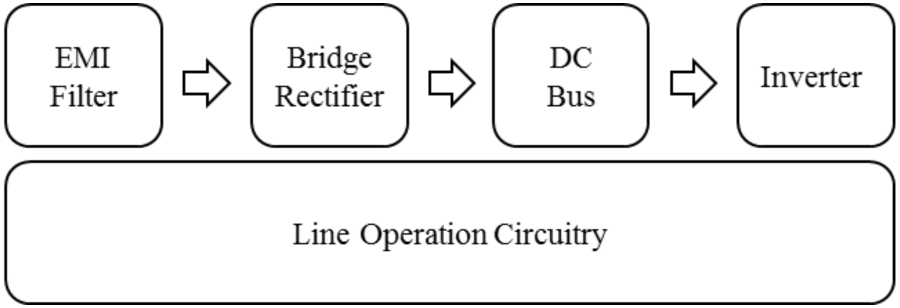


System solution to convert fixed-speed system into variable speed.

The Inverter Drive

- Benefits:
  - Modifies a single speed system to be operated as a variable speed system
    - Cooling capacity can be modulated to match the load.
    - Reduced cyclic operation
  - Drive disengaged at high power
    - No losses due to drive electronics at high power.
    - Reduced thermal management at high power.
  - Drive allows precise acceleration of the compressor

Block diagram of a typical variable speed drive.



System solution to convert fixed-speed system into variable speed.

Approach

- The inverter drive has been experimentally tested on a unitary split system single speed air source heat pump.

- To quantify the impact of the inverter drive, the heat pump is tested before and after modification with the drive.
  - Before inverter drive:
    - Baseline system is a traditional single speed heat pump
  - After inverter drive:
    - Enabled variable speed operation of compressor and fan motors

- A **seasonal performance** testing standard has been followed to compare the performance of the heat pump before and after the inverter drive modification.

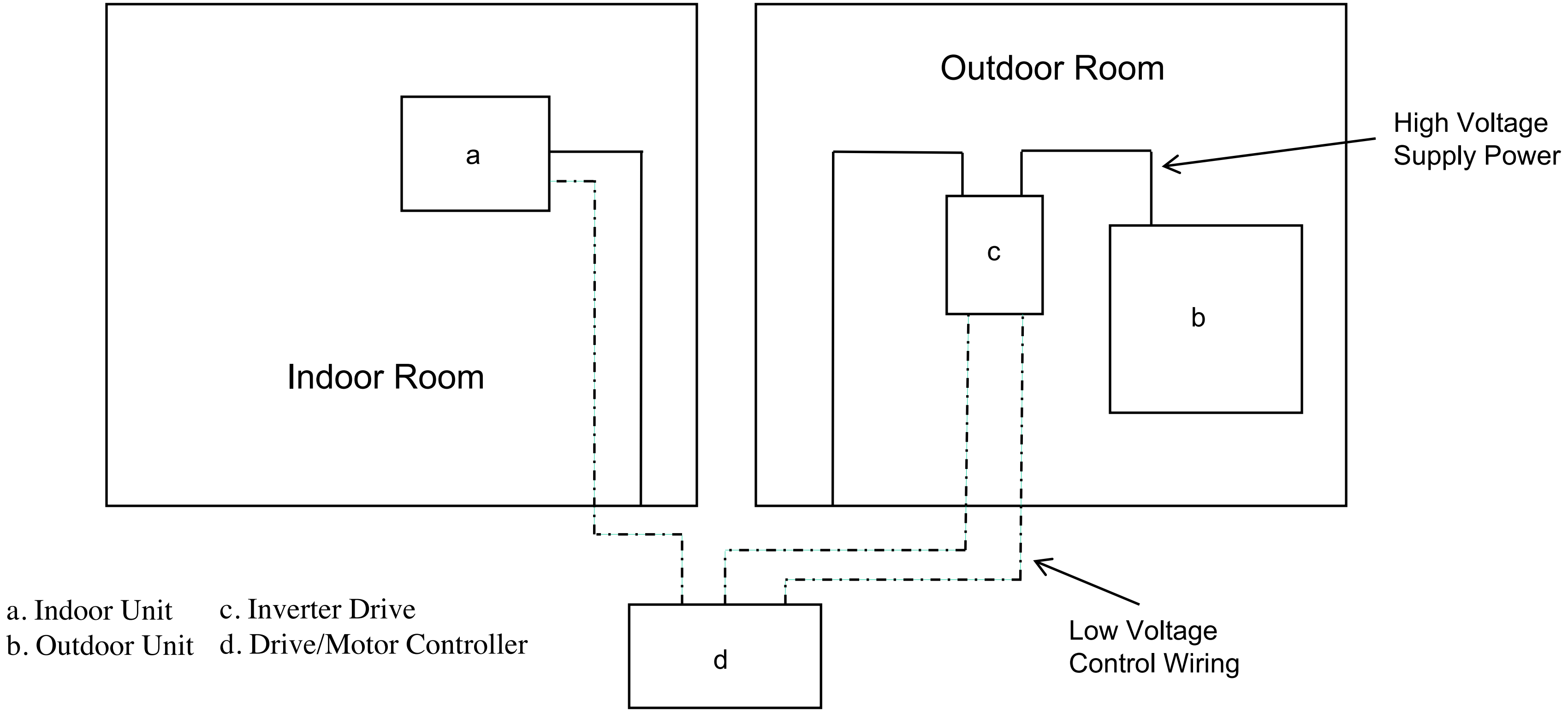
Approach

- Why a seasonal analysis?
  - The benefits of a variable speed system are realized as the load varies over the entire cooling/heating seasons.
  - A seasonal analysis is required to have a meaningful comparison between a single speed heat pump and a variable speed heat pump.

- How to measure seasonal performance?
  - SEER (Seasonal Energy Efficiency Ratio) is used as a metric of seasonal performance.
  - SEER is the cooling mode rating system of air conditioners and heat pumps in the United Sates.

Experimental Test Set Up

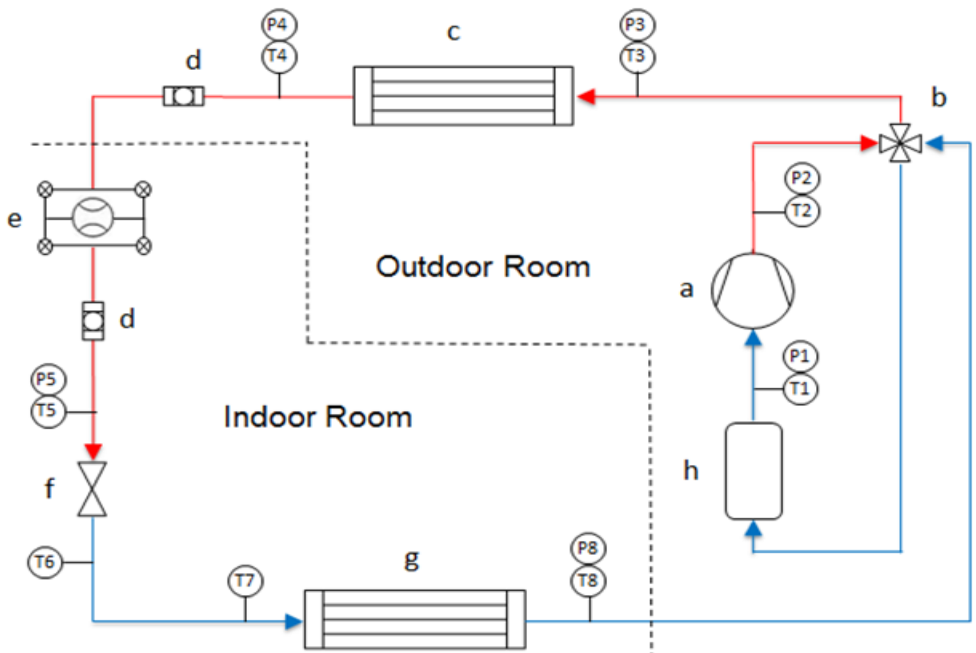
- The inverter drive and unitary split-system heat pump have been installed in the Ray W. Herrick Laboratories at Purdue University
  - The inverter drive is installed in-line between Outdoor Unit and Power Supply
  - Manual controller used to control motor speeds
    - A signal from 0-100 % load can be demanded by the controllers
  - This system allows independent control of the indoor fan, outdoor fan, and compressor motor speeds.



Schematic of Electrical Installation in Psychrometric Chambers

Experimental Test Set Up

- The heat pump has been instrumented to compute the cooling capacity using both the refrigerant and air enthalpy methods.



a. Compressor
b. Four-way reversing valve
c. Condenser
d. Sight glass
e. Mass flow meter
f. Thermostatic expansion valve
g. Evaporator
h. Accumulator

Schematic of refrigerant-side instrumentation

Experimental Test Set Up

- Two different systems with different compressor types have been tested with the inverter drive.
  - System #1
    - 5 ton single speed heat pump
    - Scroll compressor
    - Nominal indoor air flow rate of 1750 cfm
    - Baseline SEER of 14.0
  - System #2
    - Replaced the scroll compressor of system # 1
      - 4 ton rotary compressor
    - All other system components remain the same

Variable Speed Test Matrix

- SEER rating for a given system is determined at declared maximum, minimum, and intermediate component speeds

- Goal is to optimize SEER as a function of component speeds
  - Maximum speed and full-load operation will not change from the baseline system
  - Intermediate speed determined as a function of minimum speed
  - We can therefore define a set of operating conditions based on the minimum speed used.

- Inverter drive system focused on variable speed tests E_V, B_1, and F_1

Test description	Air entering indoor unit °F/°C		Air entering outdoor unit °F/°C		Compressor speed	Air volume rate
	Dry–bulb	Wet–bulb	Dry–bulb	Wet–bulb		
A_2 (required)	80/26.7	67/19.4	95/35	75/23.9	Maximum	Full–load
B_2 (required)	80/26.7	67/19.4	82/27.8	65/18.3	Maximum	Full–load
E_V (required)	80/26.7	67/19.4	87/30.6	69/20.6	Intermediate	Intermediate
B_1 (required)	80/26.7	67/19.4	82/27.8	65/18.3	Minimum	Minimum
F_1 (required)	80/26.7	67/19.4	67/19.4	53.5/11.9	Minimum	Minimum
G_1 (optional)	80/26.7	< 57/13.9	67/19.4	---	Minimum	Minimum
I_1 (optional)	80/26.7	< 57/13.9	67/19.4	---	Minimum	

[ANSI/AHRI Standard 210/240-2008]

Review of SEER Calculation

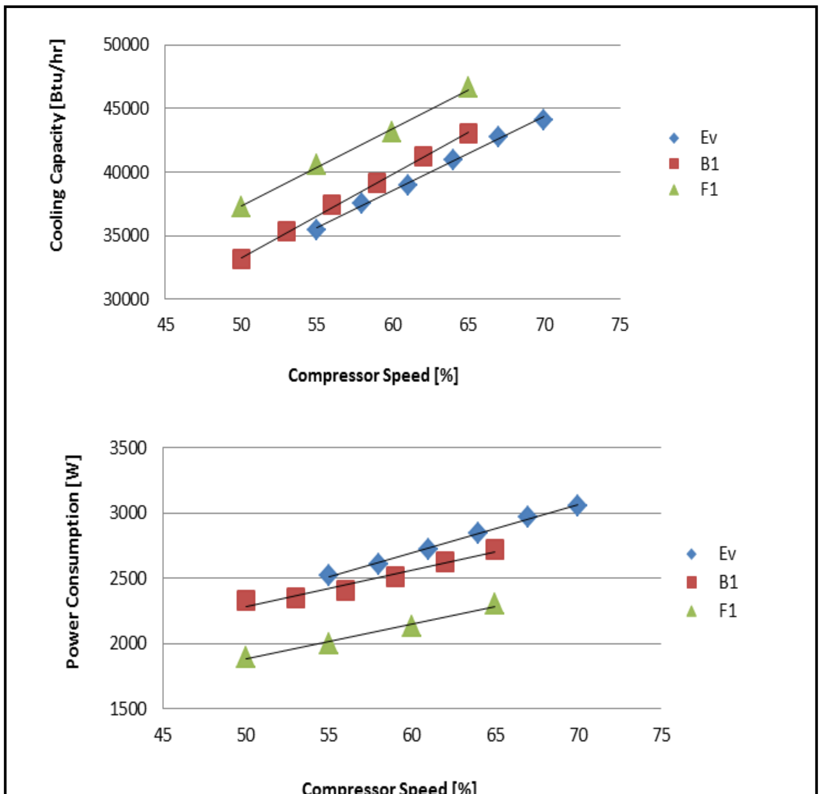
- SEER is calculated as the sum of cooling delivered over the sum of power consumed for the entire cooling season
- The cooling season is divided into 8 bins, each defined by:
  - Representative temperature
  - Fraction of seasonal operating hours

$$\mathrm{SEER} = \frac{\sum_{j=1}^{8} q_c(T_j)}{\sum_{j=1}^{8} e_c(T_j)}$$

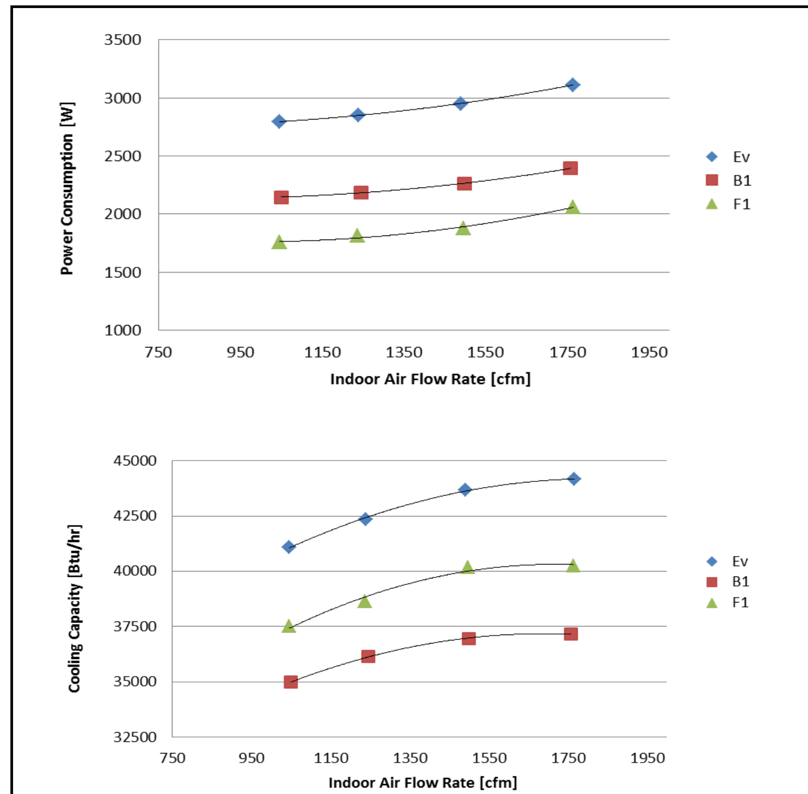
Bin Number, j	Bin Temperature Range ºF/ºC	Representative Bin Temperature ºF/ ºC	Fraction of Total Temperature Bin Hours
1…………………	(65-69)/(18.3-20.6)	67/19.4	0.214
2…………………	(70-74)/(21.1-23.33)	72/22.2	0.231
3…………………	(75-79)/(23.8-26.1)	77/25	0.216
4…………………	(80-84)/(26.7-28.9)	82/27.8	0.161
5…………………	(85-89)/(29.4-31.7)	87/30.6	0.104
6…………………	(90-94)/(32.2-34.4)	92/33.3	0.052
7…………………	(95-99)/(35-37.2)	97/36.1	0.018
8…………………	(100-104)/(37.8-40)	102/38.8	0.004

Results – System #1, Scroll

- Variable Compressor Speed Testing:
  - Determined the optimum minimum compressor speed at full speed fan operation
- Variable Indoor Fan Speed Testing:
  - Varied the indoor flow rate at the minimum compressor speed determined in the variable compressor speed testing
- In both cases, cooling capacity and power consumption vs compressor speed curves were generated as inputs to the SEER Calculation.



Variable Compressor Speed Testing



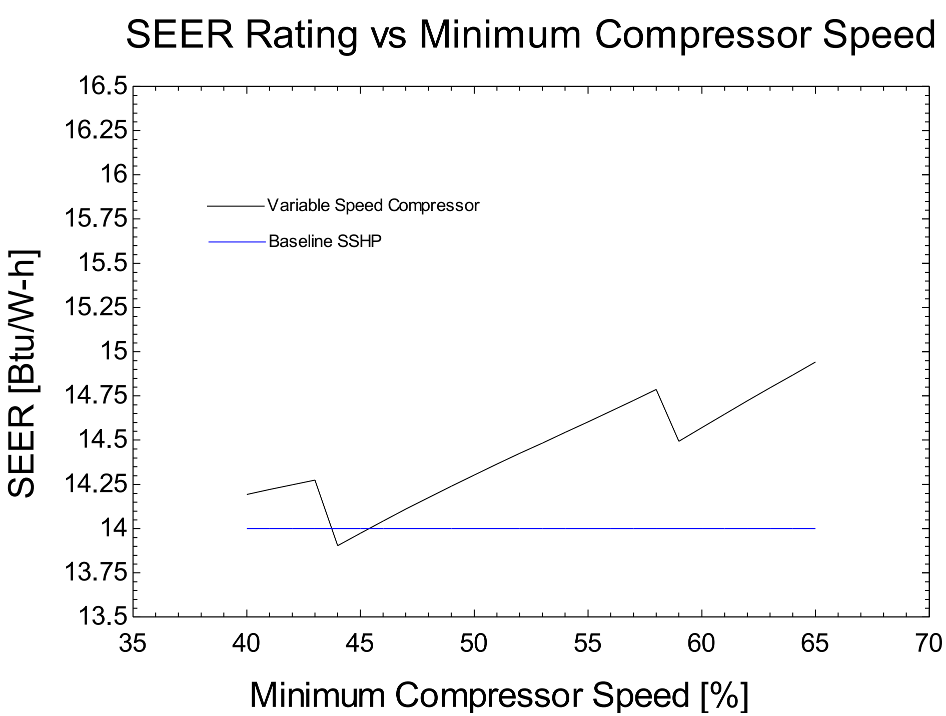
Variable Indoor Air Flow Rate Testing

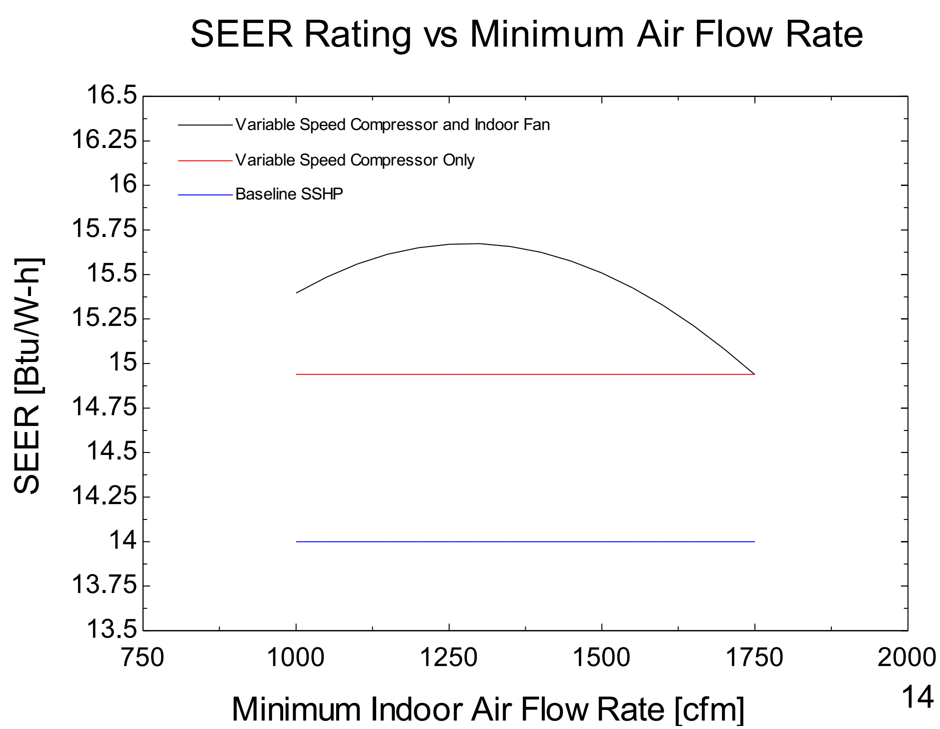
Results - Scroll

- Both variable speed component tests led to seasonal efficiency improvements

- The scroll compressor did not show significant improvement at compressor speeds lower than 45%
- The minimum compressor speed resulting in the highest SEER is theoretically > 65%

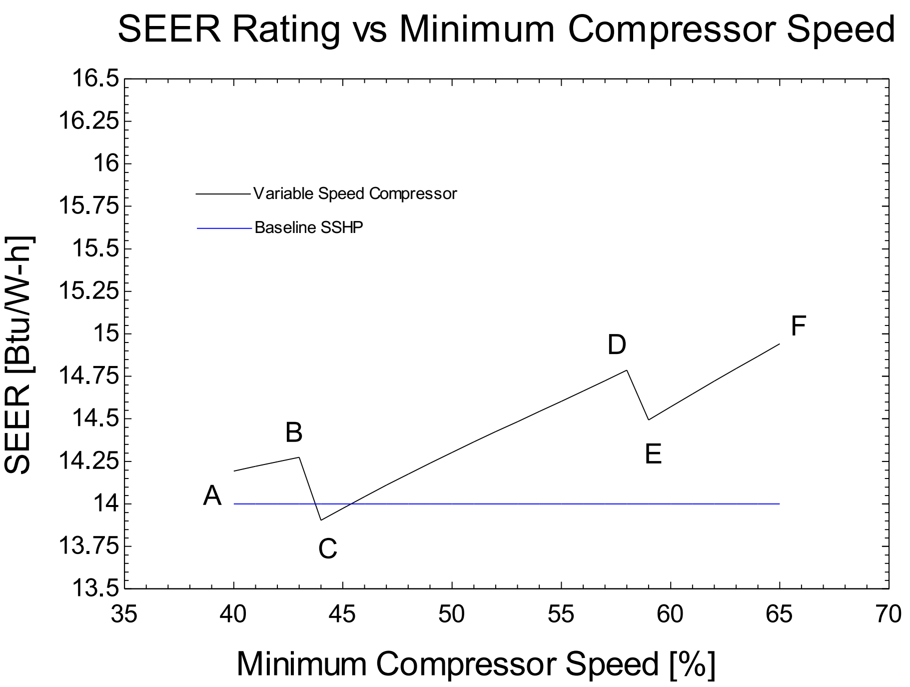
- The variable indoor air flow rate testing was able to identify the optimum indoor air flow rate to maximize SEER at the selected compressor speed.
  - Compressor speed for variable indoor air flow rate testing chosen from compressor speed optimization





Results - Scroll

- Discontinuities in curve can be explained by the SEER calculation method.
  - 8 temperature bins are used to define the cooling season.
  - Across a discontinuity, one of these bins changes operating mode



Bin #	Bin Temp	Operating Mode		
		A-B	C-D	E-F
[-]	[ºF/ ºC]	[-]	[-]	[-]
1	(65-69)/(18.3-20.6)	min	min	min
2	(70-74)/(21.1-23.33)	min	min	min
3	(75-79)/(23.8-26.1)	min	min	min
4	(80-84)/(26.7-28.9)	int	min	min
5	(85-89)/(29.4-31.7)	int ↘	int	min
6	(90-94)/(32.2-34.4)	int	int ↘	int
7	(95-99)/(35-37.2)	int	int	int
8	(100-104)/(37.8-40)	max	max	max

Summary of Results - Scroll

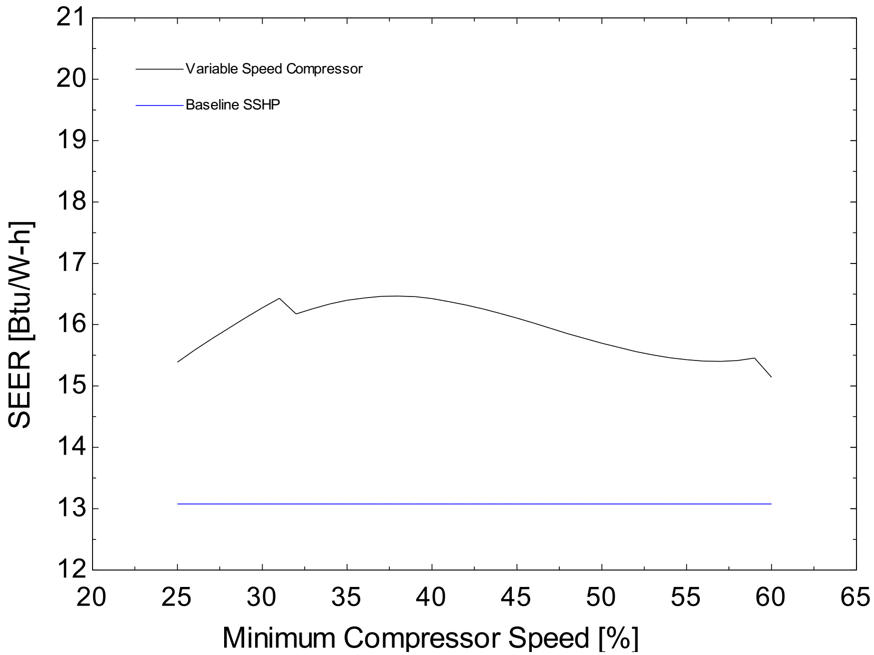
- SEER Improvement using Optimization Method
  - Variable Speed Compressor :
    - 6.71% improvement from baseline
    - 65% Minimum Compressor Speed
  - Combined Variable Speed Compressor and Indoor Fan:
    - 11.93% improvement from baseline
    - 1250 cfm

Test Case	SEER	Improvement to SSHP Baseline		Improvement to VSHP with only Variable Compressor Speed	
[-]	[-]	[-]	[%]	[-]	[%]
Baseline………………………………………………	14.0	-	-	-	-
Variable Compressor Speed………………………	14.94	0.94	6.71	-	-
Variable Compressor and Indoor Fan Speed……	15.67	1.67	11.93	0.73	4.89

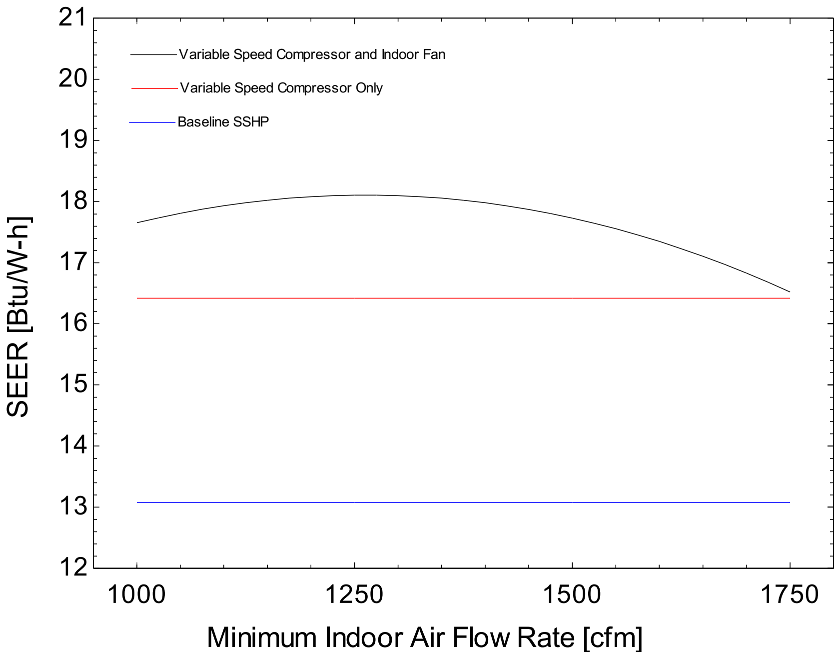
Results - Rotary

- Both variable speed component tests led to seasonal efficiency improvements
- The rotary compressor was tested reliably to speeds as low as 25%
- The minimum compressor speed resulting in the highest SEER is ~38%
- A minimum air flow rate of 1250 cfm was again found to be the optimum indoor air flow rate for SEER improvement
  - Minimum compressor speed of 40% used in variable indoor fan speed testing

SEER Improvement with Variable Speed Compressor



SEER Improvement with Variable Speed Compressor and Indoor Fan



Summary of Results - Rotary

- SEER Improvement using Optimization Method
  - Variable Speed Compressor :
    - 25.8% improvement from baseline
    - 40% Minimum Compressor Speed
  - Combined Variable Speed Compressor and Indoor Fan:
    - 38.4% improvement from baseline
    - 1250 cfm

Test Case	SEER	Improvement to SSHP Baseline		Improvement to VSHP with only Variable Compressor Speed	
[-]	[-]	[-]	[%]	[-]	[%]
Baseline……………………………………………	13.08	-	-	-	-
Variable Compressor Speed………………………	16.46	3.38	25.8	-	-
Variable Compressor and Indoor Fan Speed……	18.10	5.02	38.4	1.64	9.96

Scroll vs Rotary Systems

- Rotary system shows better improvement with inverter drive
  - Able to achieve lower speeds
  - Lower part load capacity results in less seasonal cyclic operation

Test Case	Scroll System		Rotary System	
	SEER	Improvement to SSHP Baseline	SEER	Improvement to SSHP Baseline
[-]	[-]	[%]	[-]	[%]
Baseline………………………………………………	14.0	-	13.08	-
Variable Compressor Speed………………………	14.94	6.71	16.46	25.8
Variable Compressor and Indoor Fan Speed……	15.67	11.93	18.10	38.4

Conclusions

- The inverter drive offers a unique solution to the control of single speed systems.
  - Provides a non-invasive solution for the retrofit of existing single speed systems
  - Certain benefits over existing variable speed drives also make it a good candidate for new variable speed systems

- Experimental results show that the inverter drive improved the SEER of both baseline systems baseline by enabling the use of a variable speed compressor and fans.
  - The rotary compressor system showed better improvement due to the ability to operate at lower speeds

Questions?

Thank You