2004

Transient Modeling of Vapor Compression Refrigeration Systems Using Measured Compressor COP

Steve Pfister
The Coca-Cola Company

TRANSIENT MODELING OF VAPOR COMPRESSION REFRIGERATION SYSTEMS USING MEASURED CYCLE COP

Steve PFISTER

The Coca-Cola Company
Atlanta, Georgia, USA
Tel 404-676-2825
Fax 404-515-5333
stpfister@na.ko.com

ABSTRACT

Many analytical models are used to simulate steady-state performance of refrigeration systems, but do not predict performance during transient operation. This paper presents a method for predicting the cooling performance of vapor compression refrigeration systems during transient and various ambient conditions based on established steady-state performance. I characterized the performance of existing refrigeration systems and components during cooling from initial ambient temperature and steady state operation. I derived an empirical relation between the measured compressor COP and Carnot COP during initial pull down and steady state operation. When compared, the measured compressor COP and formulated compressor COP (based on Carnot COP) correlate within 10% over most of the transient operation. I demonstrated similar correlations for both R134a and CO2 refrigeration systems. I created a transient model based on the Carnot COP calculation to predict temperatures inside a beverage cooler within 2 C of test results.

1. INTRODUCTION

This paper presents transient test measurements that show a good correlation between Carnot COP times a constant and cooling system COP. This correlation indicates that the parameters (Th and Tc) related to Carnot COP are prevalent during transient conditions, and other parameters have much less impact to the system COP during transient conditions. These other parameters (i.e. charge, heat exchanger UA, high side pressure) remain fairly constant (B) once established for a given system. For the equipment studied in this paper, the load is beverage cans cooling from ambient temperature to the desired temperature.

Carnot COP $$COPct = Tc / (Th - Tc) \quad (1)$$

Compressor COP $$COPcp = Q'ref/Pcp \quad (2)$$

Compressor COP $$COPcp = COPct / B \quad (3)$$

Cooling System COP $$COPref = Q'ref/(Pcp + Pefan + Phfan) \quad (4)$$

Using the measured compressor COP during steady state, and applying the constant B to Carnot COP, the compressor COP can be estimated over transient conditions based on the evaporator and condenser temperatures. A transient analysis for refrigeration systems can be simplified by using estimated heat exchanger performance and the estimated compressor COP as a function of Tc & Th. Equation (2) is not equivalent to the conventional compressor COP, but an estimate based on cycle cooling & compressor work. This allows you to use a compressor COP in a model, then add the fan power separately. This is useful when 1) applying it to systems using different fans & heat exchangers (sizing & optimization) & 2) Modeling off & on cycles during SS operation.

2. TEST MEASUREMENTS & CALCULATIONS

2.1 Test Conditions

The test was conducted in a chamber with the following values for ambient temperature and relative humidity.

Table 1 - Test Conditions

	Sample #1, Ta=33 C		**Sample #1, Ta=42 C**		**Sample #2, Ta=33 C**	
	Ambient Temp. (C)	Relative Humidity	Ambient Temp. (C)	Relative Humidity	Ambient Temp. (C)	Relative Humidity
Minimum	33.1	64.1 %	41.3	47.6 %	30.6	59.7 %
Average	33.7	65.0 %	41.9	73.3 %	32.7	68.6 %
Maximum	34.2	68.5 %	42.4	106.0 %	34.9	70.0 %

2.2 Equipment Tested

The equipment for Sample #1 tested was a glass door merchandiser (cooler) holding 567 cans of beverage. The cooler was designed with a removable, bottom mounted, R134a refrigeration cassette. Sample #2 was a CO2 cassette based refrigeration cooler holding 576 cans of beverage.

2.3 Test Data & Calculations

The following table summarizes the data that was used from the testing, and the calculated variables. The data was taken over 1minute intervals throughout the test period.

Table 2 - Test Data & Calculated Variables

Measured Test Data			**Calculated Variables**		
Description	Nomenclature	Unit(s)	Description	Nomenclature	Unit(s)
Ambient Temp.	Ta	(C)	Average Product Temp.	Tp(n)	(C)
Can Product Temp.	Tp(c)	(C)	Cabinet Air Temp.	Tcab	(C)
Condenser Temp.	Th	(C)			
Evaporator Temp.	Tc	(C)	Carnot COP	COPct	(-)
Supply Temp.	Tsup	(C)	Compressor COP	COPcp	(-)
Return Temp.	Trtn	(C)			
Compressor Power	Pcp	(W)	Product Heat Transfer Rate	Q'p	(W)
Evaporator Fan Power	Pefan	(W)	Cabinet Heat Loss	Q'cab	(W)
Condenser Fan Power	Phfan	(W)	Refrigeration Cooling	Q'ref	(W)
Internal Lighting Power	Plit	(W)			
Time	T	(sec)	Cabinet UA	UAcab	(W/C)
Time step	N	(min)			

All calculations are performed for each interval (each minute) of the test data. The product temperatures are averaged. Thermocouples are placed on the cans according to Coca-Cola certification test procedures. The average product temperature is calculated where C = number of cans of beverage.

$$Tp = (Tp1 + Tp2 + Tp3 + \ldots.\ Tp_C) / C \quad (5)$$

The Carnot COP was calculated for each interval of the test data using equation (1).

$$COPct = Tc / (Th - Tc) \quad (1)$$

The Compressor COP was calculated for each interval of the test data.

Compressor COP $COPcp = Q'ref/Pcp$ (2)

Refrigeration Cooling $Q'ref = Q'p - Q'cab - Pefan - Plit$ (6)

Product Cooling $Q'p = mCp\cdot(Tp_N - Tp_{N-1})/(t_N - t_{N-1})$ (7)

Cabinet Heat Loss $Q'cab = UAcab \cdot (Ta - Tcab)$ (8)

2.4 Test Results – Sample #1

For cooler test #1, the measured return air was considered to be equivalent to the average cabinet air temperature. (Tcab = Trtn). The Product Heat Capacity is

$$mCp = (567\ \text{cans})\cdot(.355\ \text{liter/can})\cdot(1\ \text{kg/liter})\cdot(4.186\ \text{kJ/kg K}) = 842.6\ \text{kJ/K} \qquad (9)$$

Condenser temperature, Th was measured with a thermocouple on the condenser inlet tubing. Evaporator temperature, Tc was measured with a thermocouple on the evaporator outlet tubing. Cabinet UA, UAcab, has been previously determined using the test data during compressor off cycles. For cooler test #1, the measured Compressor COP and estimated Compressor COP are plotted to show the correlation. The constant scale factor, B was assigned a value of 4.6 (see Equation (3)).

Table 3 - Estimated & Calculated Compressor COPs, B = 4.6

Elapsed Time (hours)	Product Average (C)	Tc (C)	Th (C)	**Carnot COP /B** (K/K)	**Meas. COPcp**	% Diff
1.20	26.18	16.60	39.90	**2.70**	**2.28**	19%
3.27	19.16	5.41	38.86	**1.81**	**1.77**	2%
5.33	14.08	2.85	37.82	**1.72**	**1.60**	7%
7.40	10.11	-3.30	37.06	**1.45**	**1.47**	-2%
9.47	6.95	-5.19	36.78	**1.39**	**1.43**	-3%
11.53	4.35	-6.89	36.30	**1.34**	**1.38**	-3%
13.60	2.14	-8.45	35.57	**1.31**	**1.38**	-6%
14.63	1.19	-9.20	37.46	**1.23**	**1.29**	-4%
					Average Difference	1%

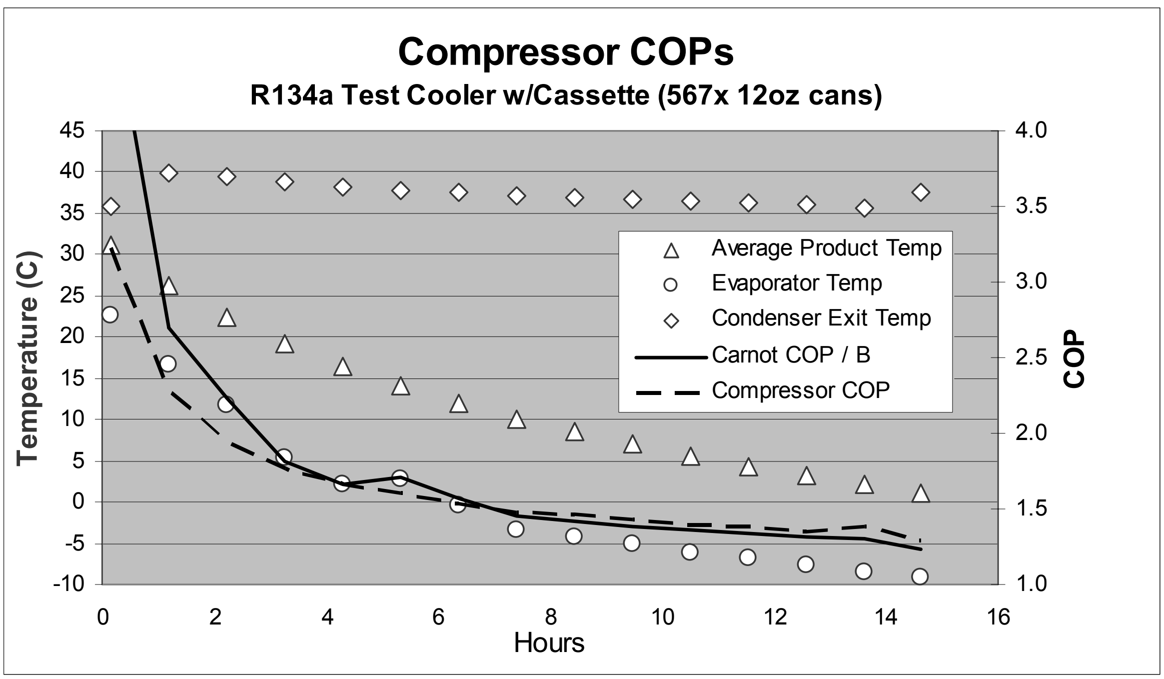

Figure 1 - Estimated & Calculated Compressor COPs, B = 4.6

Using the measured condenser exit for Th resulted in a very similar COP curve. Using the measured compressor discharge temperature for Th and B = 4.0 resulted in a closer correlation during the first two hours.

2.5 Test Results – Sample #2

For cooler test #2, the measured return air was considered to be equivalent to the average cabinet air temperature. (Tcab = Trtn). The Product Heat Capacity is

$$mCp = (576\text{ cans})\cdot(.355\text{ liter/can})\cdot(1\text{ kg/liter})\cdot(4.186\text{ kJ/kg K}) = 856.0\text{ kJ/K} \quad (9)$$

Gas Cooler temperature, Th was measured from the gas cooler exit tubing. Evaporator temperature, Tc was measured with a thermocouple on the evaporator exit tubing. Cabinet UA, UAcab, has been previously determined using the test data during compressor off cycles. For cooler test #2, the measured Compressor COP and estimated Compressor COP are plotted to show the correlation. The constant scale factor, B was assigned a value of 6.2.

Table 4 -Estimated & Calculated Compressor COPs, B = 6.2

Elapsed Time (hours)	Product Average (C)	Tc (C)	Th (C)	**Carnot COP /B (K/K)**	**Meas. COPcp**	% Diff
0.00	31.36	32.06	32.11	**3.00**	**2.50**	20%
1.55	23.43	6.44	38.19	**1.42**	**1.59**	-11%
3.10	17.90	2.54	37.97	**1.25**	**1.25**	0%
4.65	13.82	0.05	37.41	**1.18**	**1.10**	7%
6.20	10.52	-2.09	37.30	**1.11**	**1.03**	7%
7.75	7.83	-3.72	36.98	**1.07**	**0.94**	14%
9.30	5.39	-6.24	36.86	**1.00**	**1.07**	-7%
10.33	4.01	-7.65	36.76	**0.96**	**1.05**	-8%
11.37	2.75	-8.87	36.43	**0.94**	**0.93**	1%
					Average Difference	3%

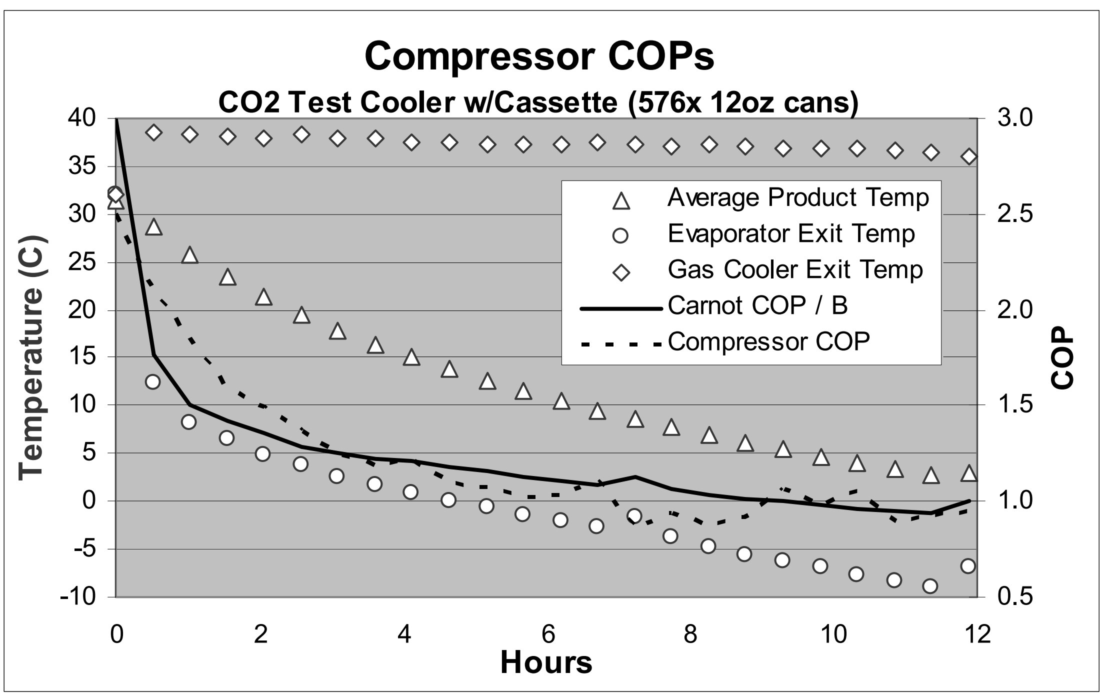

Figure 2 - Estimated & Calculated Compressor COPs, B = 6.2

3. TRANSIENT SIMULATION USING CARNOT COP

3.1 Simulation – Sample #1

A simple transient spreadsheet model has been created using the established constant, B.

Table 5 – Simulation of 567 can Cooler using Carnot COP / B, B = 4.6

SS COP Measurement		
Description	**Value**	**U/M**
Evaporator Temp	-7.1	C
Condenser Temp	36.1	C
Compressor SS COP	1.34	
Carnot SS COP	6.16	
Factor	4.60	
Calculated & Estimated Parameters		
Heat Cpacity, mCp	842579	J/K
Nominal Compressor Power	400	W
Maximum Compressor Power	500	W

Performance Parameters (from Test)		
Description	**Value**	**U/M**
Ambient Air Temp	32.2	C
Off Set Point Temp - Retn Air*	0	C
On Set Point Temp - Retn Air*	5	C
Cabinet UA	8.75	W/C
Can to air UA	200	W/C
Light Power	28	W
Number of cans	567	
Mcan	0.355	kg
Cp_KO	4186	J/kg-K
Evaporator UA	70	W/K
Cold Side Fan Power	52	W
Condenser UA	400	W/C
Hot Side Fan Power	40	W

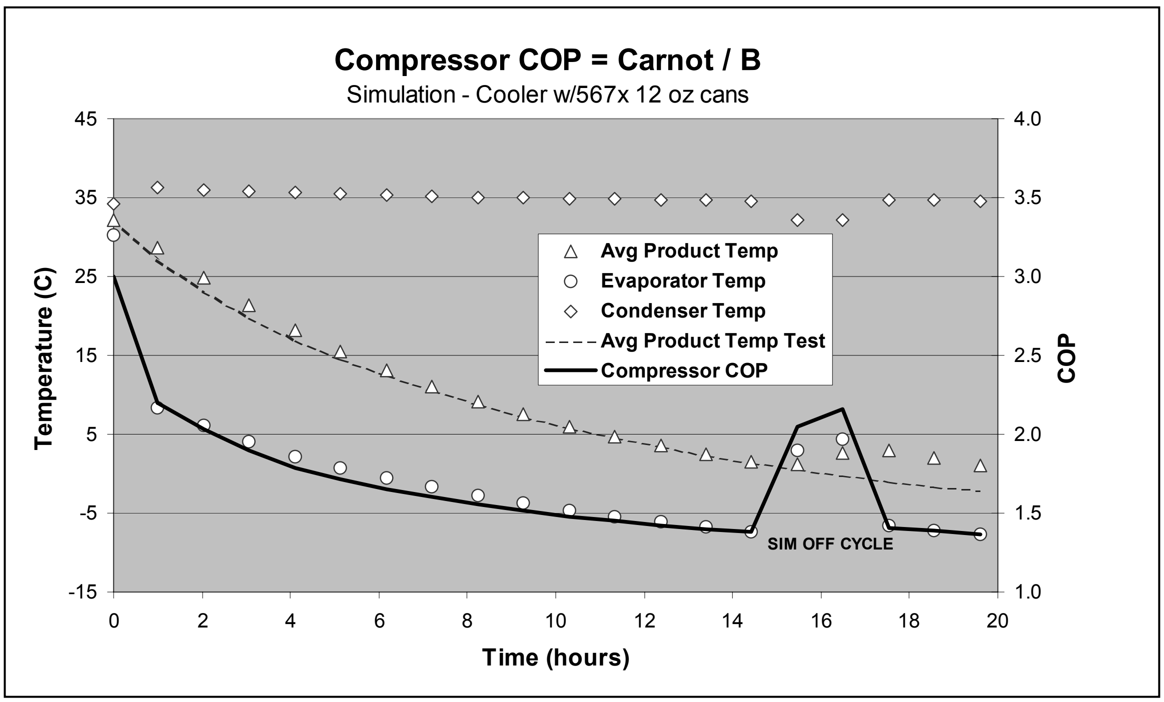

Figure 3 - Simulation of 567 can Cooler using Carnot COP / B, B = 4.6

An additional simulation was performed for Ta = 41.9 C with a similar correlation to test results.

3.2 Simulation – Sample #2

The transient spreadsheet model was also applied to Sample #2 using constant, B = 6.2.

Table 6 - Simulation of 576 can Cooler using Carnot COP / B, B = 6.2

SS COP Measurement		
Description	**Value**	**U/M**
Evaporator Temp	-7.0	C
Condenser Temp	36.9	C
Compressor SS COP	0.98	
Carnot SS COP	6.07	
Factor	6.20	

Calculated & Estimated Parameters		
Description	**Value**	**U/M**
Heat Cpacity, mCp	855953	J/K
Nominal Compressor Power	575	W
Maximum Compressor Power	750	W

Performance Parameters (from Test)		
Description	**Value**	**U/M**
Ambient Air Temp	32.2	C
Off Set Point Temp - Retn Air*	-0.5	C
On Set Point Temp - Retn Air*	5	C
Cabinet UA	7.5	W/C
Can to air UA	110	W/C
Light Power	0	W
Number of cans	576	
Mcan	0.355	kg
Cp_KO	4186	J/kg-K
Evaporator UA	110	W/K
Cold Side Fan Power	25	W
Gas Cooler UA	320	W/C
Hot Side Fan Power	20	W

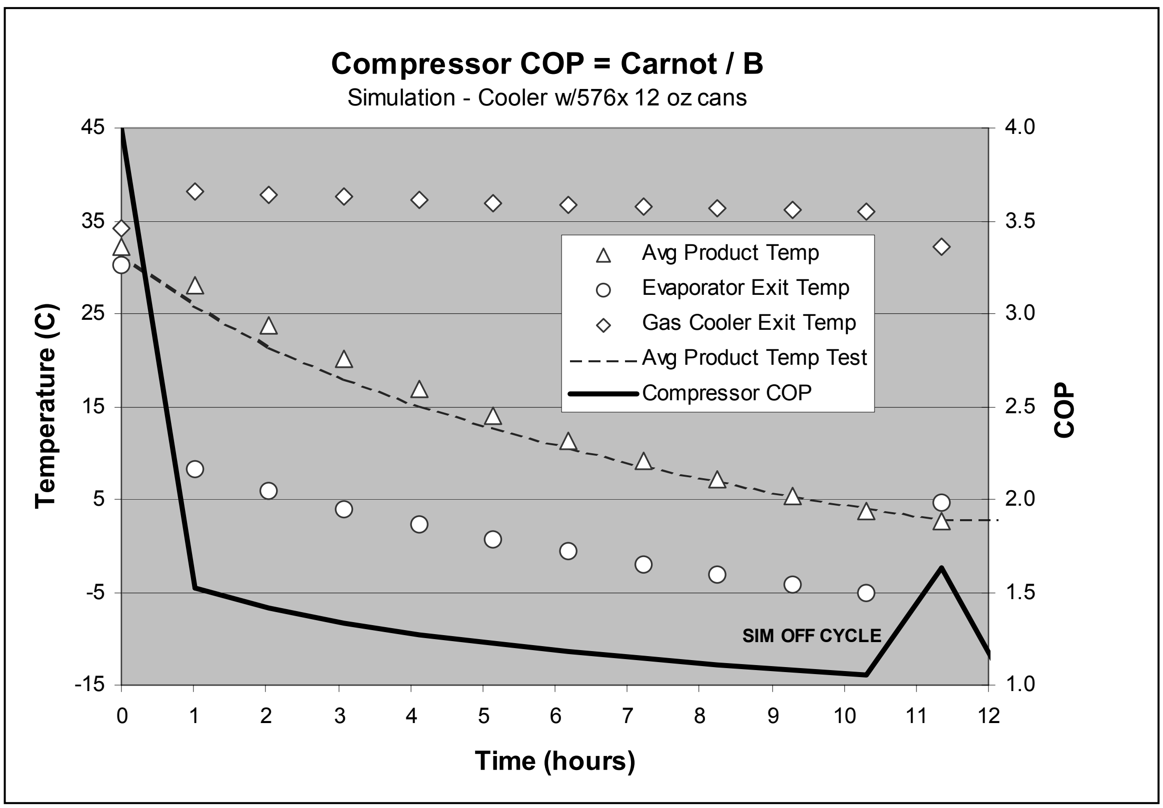

Figure 4 - Simulation of 576 can Cooler using Carnot COP / B, B = 6.2

4. CORRELATION OF CARNOT COP / B

The following tables summarize the difference in predicted product temperatures and test results.

Table 7 - Correlation of Simulation Using Carnot COP to Test Temperatures

Test Sample #1, Ta = 32 C			
	Average Product Temperature		
Elapsed Time	Test	Simulation	Diff
6.2 hrs	12.4 C	13.1 C	0.69 C
12.0 hrs	3.4 C	3.5 C	0.10 C

Test Sample #2			
	Average Product Temperature		
Elapsed Time	Test	Simulation	Diff
6.2 hrs	10.5 C	11.4 C	0.85 C
12.0 hrs	2.72 C	2.74 C	0.02 C

Test Sample #1, Ta = 41.9 C			
	Average Product Temperature		
Elapsed Time	Test	Simulation	Diff
7.0 hrs	17.7 C	20.1 C	2.4 C
14.0 hrs	7.8 C	9.7 C	1.9 C
20.0 hrs	3.8 C	5.2 C	1.4 C

5. CONCLUSIONS

5.1 Test Data Comparisons

After a cooling system starts, there is a brief period of time during which the condenser or gas cooler warms up above the ambient. During this period, compressor COP calculations based on Th & Tc are very inconsistent. After this initial period, the evaporator typically continues to cool relative to the temperature of the load. For the equipment studied in this paper, the load is beverage cans cooling from the ambient temperature to the desired temperature. When compared, the measured compressor COP and formulated compressor COP (based on Carnot COP) correlate within 10% over most of the transient operation. When the evaporator experiences frosting, Tc variations cause some error when using Tc from test results to calculate compressor COP. Outside of startup period and frosting, the trends in measured compressor COP are reflected by the Carnot COP calculation.

5.2 Simulations

Using Carnot COP equation for simulating vapor compression refrigeration system performance in transient conditions has shown to correlate to test results within 2 C for various loads, working, fluids, and ambient temperatures. The modeling techniques were very simple and introduced error not associated with the compressor COP calculation, but was still useful for rough estimates and sizing components. Applying the compressor COP Equation (3) in a more sophisticated model would be even more effective.

NOMENCLATURE

Q’	Cooling Capacity / Heat Transfer	(W)
Q	Heat Transfer Energy	(kW-hr)
P	Electrical Power	(W)
E	Electrical Energy	(kW-hr)
T	Temperature	(C) or (K)
UA	Heat Transfer Coefficient	(W/C)
COP	Coefficient of Performance	(-)
Cp	Specific Heat Capacity	(kJ/kg-K)
m	Mass	(kg)
B	Constant	(-)
h	Enthalpy	(kJ/kg)
dh	Change in Enthalpy	(kJ/kg)
t	Time	(seconds)
C	Number of beverage cans	(-)

Subscripts	
a	Ambient
c	Evaporator (cold)
cab	Cabinet
efan	Evaporator Fan
cp	Compressor
ct	Carnot
evap	Evaporator (cold)
h	Condenser (hot)
hfan	Condenser Fan
lit	Lights
p	Product (beverage cans)
ref	Refrigeration system
rtn	Return air
sup	Supply Air
N	Time step – one minute intervals

REFERENCES

[1] Hubacher, B., Groll, E., December, 2002, *Measurement of Performance of Carbon Dioxide Compressors,* Ray W. Herrick Laboratories, Purdue University

[2] Incropera, F. P and DeWitt, D. P., 1985. *Fundamentals of Heat and Mass Transfer*, 2nd Edition, John Wiley & Sons, New York

[3] Veje, C., 2003. *CO2 Workshop at Danfoss October 2003*

ACKNOWLEDGEMENT

All testing has been performed by The Coca-Cola Company in Atlanta, GA. Thanks to Coca-Cola test engineers Brad Anderson, Brian Didier for support.