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# Performance Potential of $CO_2$ Cycle with a Linear Compressor

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## ABSTRACT

This paper describes the performance potential of a transcritical $CO_2$ cycle with a linear compressor for medium temperature refrigeration systems. Hermetic linear compressors have been previously developed for subcritical cycles especially for small capacity refrigeration systems and have demonstrated their performance potential as compared to conventional compressors. To investigate the performance of a transcritical $CO_2$ cycle with a linear compressor for medium temperature refrigeration systems, cycle simulation was carried out. The performance of transcritical $CO_2$ cycles was simulated for medium temperature refrigeration systems by using the compressor efficiencies measured. The simulated results show that the cooling capacity is 235 W at 40.5°C ambient temperature and the COP is 1.31 at 32.2°C ambient temperature. The heat exchangers were then designed using the heat exchanger design software. The results show that the $CO_2$ linear compressor together with suitably designed heat exchangers can be successfully applied to medium temperature refrigeration systems.

## INTRODUCTION

Three major international food and beverage companies initiated a *Refrigerants Naturally Partnership* to replace the refrigerant hydrofluorocarbons (HFC's) with natural refrigerants and to reduce the global warming contribution from the food and drink industry and its supply chain (2004). Under the partnership five alternative technologies to current HFC based technology were investigated including hydrocarbons, carbon dioxide, Stirling, thermoacoustic and solar cooling. Among those, technologies such as hydrocarbon and carbon dioxide are already exposed in the marketplace, while others are subject to further development due to their efficiency, reliability and cost issues. The partnership's focus is to develop equipment using alternative refrigerants and while maintaining high efficiency at the same time. Moreover, the number of small capacity systems is growing faster than other capacity ranges especially in developing countries. Therefore, $CO_2$ linear compressors having small capacity range and high efficiency, have great potential in the energy efficiency of refrigeration equipment. It is the objective of the current study to design the small capacity $CO_2$ refrigeration system using a linear compressor and to investigate its performance.

## CYCLE MODELS

To model the performance of the transcritical $CO_2$ cycle, the computer model of the $CO_2$ cycle was developed. The cycle model was developed in two steps. In the first step, the compressor efficiencies were measured and correlated. In the second step, the cycle was modeled using those compressor efficiency correlations and the following assumptions for the small capacity refrigeration system:

- Cabinet air temperature is maintained at 3.3°C.
- Ambient temperature varies in three levels: 24.5°C, 32.2°C, and 40.5°C
- Evaporating temperature is maintained at -8°C.
- Degree of superheating at the evaporator outlet is 12°C to guarantee no frost formation along the

suction line (ARI, 1997).

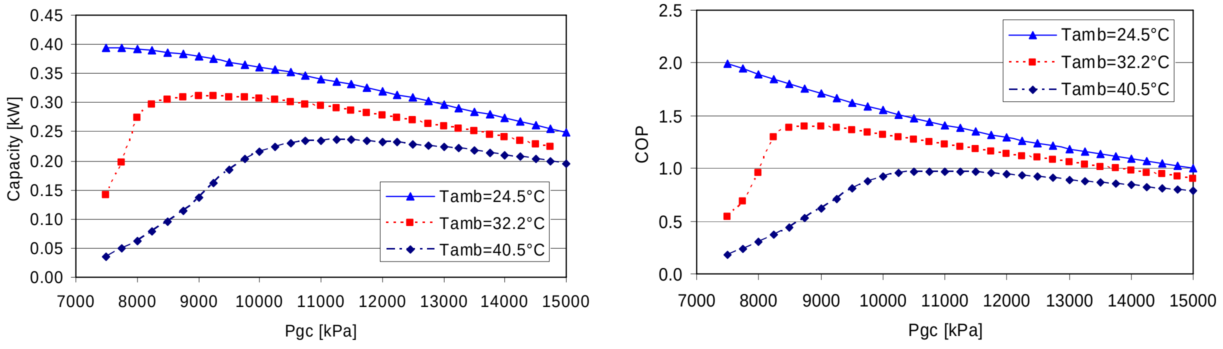
- Approach temperature at the gas cooler outlet is 3°C.
- Pressure drops in evaporator and gas cooler are 50 kPa and 100 kPa, respectively.
- Compressor displacemental volume is 0.75cc.
- Compressor speed is 3600 strokes per minute.
- Evaporator and condenser fan powers are 15W and 30W, respectively.

In the first step, two measured compressor efficiencies (compressor efficiency and volumetric efficiency) were correlated in first order linear equations as the function of the pressure radio (PR) as shown in Equation (1). For the given pressure ratio 3.0, the measured compressor and volumetric efficiency were 0.66 and 0.77.

$$\begin{aligned} \eta_{comp} &= 0.801 - 0.0477 * PR \\ \eta_{vol} &= 1.140 - 0.1224 * PR \end{aligned} \qquad (1)$$

In the evaluation of the performance potential of the cycle, the gas cooling pressure was optimized for the range of operating conditions. The calculated performance of the $CO_2$ cycle with the linear compressor is illustrated for various gas cooling pressures in Figure 1. In Table 1, the performance of the cycles at their optimum gas cooling pressure is summarized for each ambient temperature. Some observations from the results are as follows:

- The linear compressor can provide 235 W cooling capacity at 40.5°C ambient condition.
- The linear compressor can provide 1.31 Coefficient of Performance (COP) at 32.2°C ambient condition.



(a) Cooling Capacity (b) COP

**Figure 1 Simulated Performance of $CO_2$ Cycle**

**Table 1 Performance of $CO_2$ Cycle at Optimum Gas Cooling Pressure**

| $T_{amb}$ [°C] | $P_{gc,opt}$ [MPa] | Capacity [W] | COP | Power [W] | $\eta_{comp}$ | $\eta_{vol}$ | PR | $T_{dis}$ [°C] |
|---|---|---|---|---|---|---|---|---|
| 24.5 | 7.50 | 394 | 1.85 | 213 | 0.67 | 0.80 | 2.82 | 92 |
| 32.2 | 8.75 | 305 | 1.31 | 233 | 0.64 | 0.74 | 3.28 | 109 |
| 40.5 | 11.00 | 235 | 0.92 | 257 | 0.60 | 0.64 | 4.11 | 136 |

## HEAT EXCHANGER DESIGN

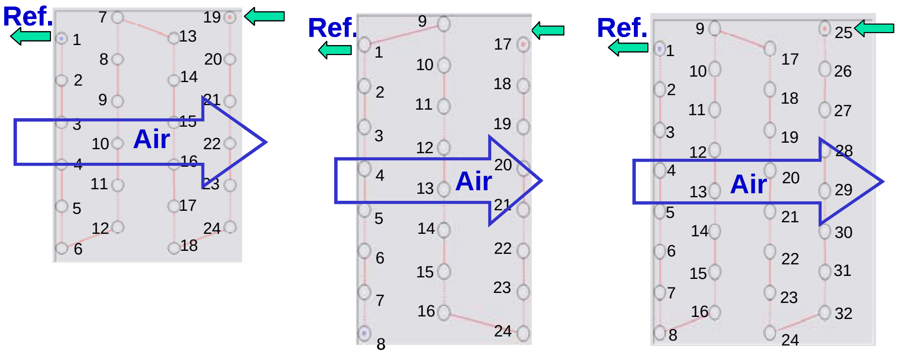
Once the cycle performance was simulated, then the next task was the design of heat exchangers, which have to satisfy the thermal requirements summarized in Table 1. Both heat exchangers were designed by using the heat exchanger design software (CEEE (1), 2005). Although the software can model both "fin-and-tube" type and 'microchannel" type heat exchangers, the current paper reports only design results of the "fin-and-tube" type heat exchangers. The evaporator and gas cooler were designed to meet the burst pressure 22 MPa and 32 MPa, respectively. In the calculations, it was assumed that the air velocity is always 1 m/s for the gas cooler and the air flow rate is always 0.0531 $m^3/s$ for the evaporator. To predict the refrigerant-side heat transfer coefficients, Gnielinski's single-phase heat transfer correlation (1976) and Gungor-Winterton's two-phase heat transfer correlation (1986) were used. Since the air-side heat transfer is determined by the type of the fins, two types of fins (corrugated fin and louvered fin) were considered. For the heat transfer correlations, Kim-Youn-Webb correlation (1997) was used for the corrugated fins; and Chang-Wang correlation (1997) was used for the louvered fin. Although the louvered fin has better air-side heat transfer coefficients than the corrugated fin, the corrugated fin was selected in the final design after considering harsh operating conditions and frost formation.

## Gas Cooler Design

To investigate the design of the gas cooler (GC) three different configurations were examined as shown in Table 2 and Figure 2. Total height of both heat exchangers is limited to the height equivalent to 12 rows by assuming both heat exchangers aligned top to bottom. One six-row height design was selected to keep the same height for both heat exchangers. Two eight-row designs were selected for the taller gas cooler and the smaller height evaporator.

**Table 2: Detailed Specifications of Three Gas Coolers**

| Column x Row | | 4 x 6 | 3 x 8 | 4 x 8 |
|---|---|---|---|---|
| Heat transfer area [$m^2$] | | 2.7 | 2.7 | 3.6 |
| Tube | Material | Copper | Copper | Copper |
| | Outside Diameter [mm] | 9.52 | 9.52 | 9.52 |
| | Thickness [mm] | 0.8 | 0.8 | 0.8 |
| | Vertical Pitch [mm] | 25 | 25 | 25 |
| | Horizontal Pitch [mm] | 21.65 | 21.65 | 21.65 |
| | Length [mm] | 400 | 400 | 400 |
| Fin | Material | Aluminum | Aluminum | Aluminum |
| | Type | Corrugated | Corrugated | Corrugated |
| | Pitch [mm] | 3.63 | 3.63 | 3.63 |
| | Thickness [mm] | 0.152 | 0.152 | 0.152 |
| | Height [mm] | 150 | 200 | 200 |
| | Depth [mm] | 86.6 | 65.0 | 86.6 |



(a) 4 x 6 (b) 3 x 8 (c) 4 x 8

**Figure 2: Configurations of Three Gas Coolers**

Modeling results are summarized in Table 3. The heat transfer rate and air-side outlet temperature distribution is shown in Table 4 and Figure 3. From these results the followings are observed:

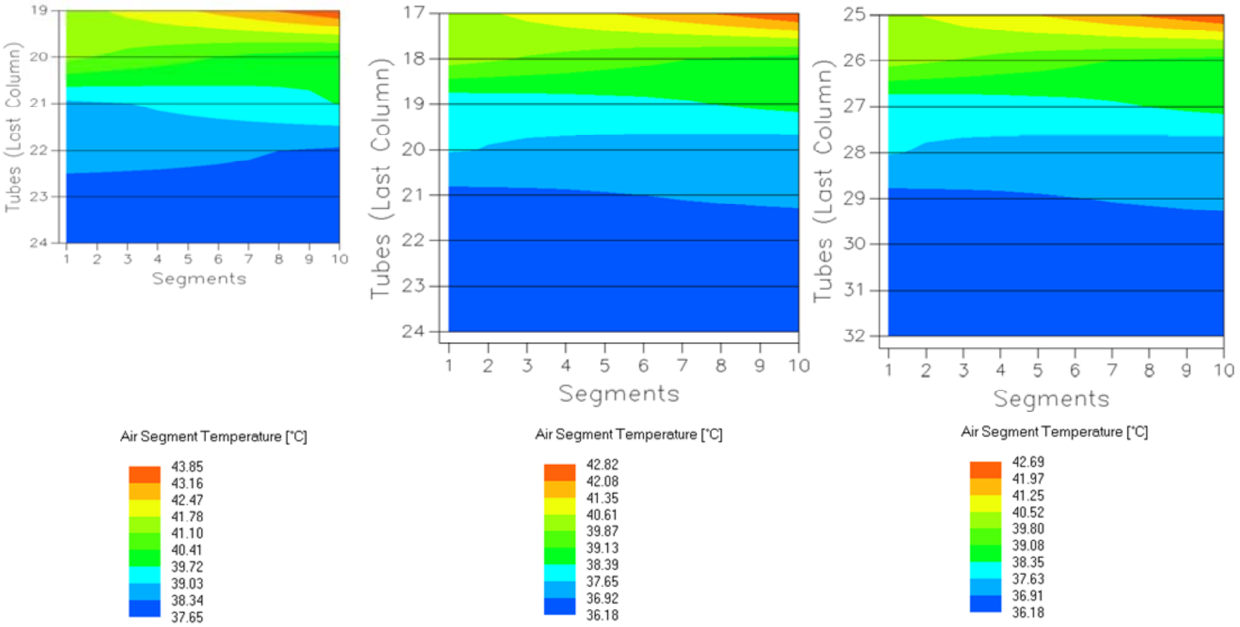
- 4 x 6 and 3 x 8 GCs can not meet the refrigerant-side capacity requirement at 24.5°C.
- 4 x 8 GC can meet the capacity requirements for all conditions.
- 3 x 8 GC performs better than 4 x 6 GC at low ambient.
- GCs with 8 rows perform better than GC with 6 rows due to the higher air flow rate.
- In the 4 x 8 GC, the first column carries only 2% of total load (Table 4). Therefore, number of column should be limited less than 5.
- Since GCs with 8 rows have a better aspect ratio than GC with 6 rows, they have better air temperature distribution (Figure 3).
- Although the performance of 3 x 8 GC is acceptable, 4 x 8 GC is selected while considering the design margin.

**Table 3: Modeling Results for the Gas Cooler**

| Column no. x Row no. | $T_{amb}$ [°C] | Capacity [W] | $PD_{gc}$ [kPa] | $T_{gc,out}$ [°C] | AFR [$m^3/s$] | $PD_{gc,air}$ [Pa] | $HTC_{air}/HTC_{ref}$ [$W/m^2$-K] |
|---|---|---|---|---|---|---|---|
| 4 x 6<br>Heat transfer area: 2.7 $m^2$ | 24.5 | 534 | 0.2 | 28.4 | 0.0610 | 12 | 57/699 |
| | 32.2 | 508 | 0.1 | 33.9 | 0.0610 | 12 | 57/502 |
| | 40.5 | 450 | 0.1 | 41.0 | 0.0610 | 12 | 57/349 |
| 3 x 8<br>Heat transfer area: 2.7 $m^2$ | 24.5 | 543 | 0.1 | 27.6 | 0.0813 | 9 | 57/690 |
| | 32.2 | 511 | 0.1 | 33.6 | 0.0813 | 9 | 57/497 |
| | 40.5 | 450 | 0.1 | 41.0 | 0.0813 | 9 | 57/347 |
| 4 x 8<br>Heat transfer area: 3.6 $m^2$ | 24.5 | 567 | 0.2 | 25.2 | 0.0813 | 12 | 57/616 |
| | 32.2 | 523 | 0.1 | 32.6 | 0.0813 | 12 | 57/475 |
| | 40.5 | 454 | 0.1 | 40.6 | 0.0813 | 12 | 57/345 |

**Table 4: Heat Transfer Rate per Column**

| Row Number | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 4 x 6 | 8% | 16% | 23% | 53% |
| 3 x 8 | 11% | 27% | 63% | - |
| 4 x 8 | 2% | 11% | 26% | 61% |



(a) 4 x 6 (b) 3 x 8 (c) 4 x 8

**Figure 3: Air-Side Outlet Temperature Profile of Gas Cooler**

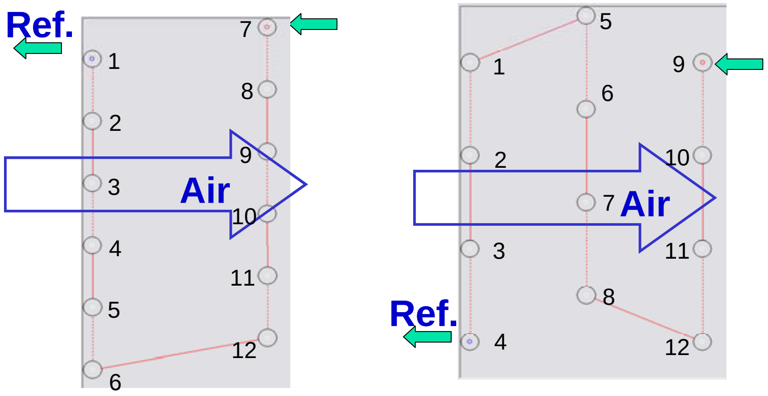
**Evaporator Design**

To investigate the design of the evaporator (EV) two different configurations were examined as shown in Table 5 and Figure 4. Two six-row height designs were selected to keep the same height for both heat exchangers. One four-row design was selected for the matched height gas cooler (4 x 8). Modeling results are summarized in Table 6. The heat transfer rate and air-side outlet temperature distribution is summarized in Table 7 and Figure 4. From these results the followings are observed:

- Both designs can meet the capacity requirements for all conditions.
- Both designs perform almost the same.
- In the 3 x 4 EV, the 1st column carries only 6% of total load (Table 6). Therefore, number of column should be limited less than 4.
- Since three column EV has less contribution from the superheated vapor area on the air cooling than the two column EV, the 3 x 4 EV has wider area in low temperature (Figure 5).

**Table 5: Detailed Specifications of Two Evaporators**

| Column x Row | | 2 x 6 | 3 x 4 |
|---|---|---|---|
| Heat transfer area [$m^2$] | | 1.3 | 1.4 |
| Tube | Material | Copper | Copper |
| | Outside Diameter [mm] | 9.52 | 9.52 |
| | Thickness [mm] | 0.6 | 0.6 |
| | Vertical Pitch [mm] | 25 | 25 |
| | Horizontal Pitch [mm] | 21.65 | 21.65 |
| | Length [mm] | 400 | 400 |
| Fin | Material | Aluminum | Aluminum |
| | Type | Corrugated | Corrugated |
| | Pitch [mm] | 3.63 | 3.63 |
| | Thickness [mm] | 0.152 | 0.152 |
| | Height [mm] | 150 | 100 |
| | Depth [mm] | 43.3 | 65.0 |



(a) 2 x 6 (b) 3 x 4

**Figure 4: Configurations of Two Evaporators**

**Table 6: Modeling Results for the Evaporator**

| Column no. x Row no. | $T_{amb}$ [°C] | Capacity [W] | $PD_{ev}$ [kPa] | $T_{ev,out}$ [°C] | AFR [$m^3/s$] | $PD_{ev,air}$ [Pa] | $HTC_{air}/HTC_{ref}$ [$W/m^2$-K] |
|---|---|---|---|---|---|---|---|
| 2 x 6<br>Heat transfer area: 1.3 $m^2$ | 24.5 | 394 | 0.3 | -1.5 | 0.053 | 5 | 54/741 |
| | 32.2 | 324 | 0.3 | 1.5 | 0.053 | 5 | 54/703 |
| | 40.5 | 248 | 0.2 | 2.5 | 0.053 | 5 | 54/502 |
| 3 x 4<br>Heat transfer area: 1.4 $m^2$ | 24.5 | 394 | 0.3 | 0.4 | 0.053 | 16 | 65/857 |
| | 32.2 | 325 | 0.3 | 1.9 | 0.053 | 16 | 65/690 |
| | 40.5 | 249 | 0.2 | 2.7 | 0.053 | 16 | 65/489 |

**Table 7: Heat Transfer Rate per Column**

| Row | 1 | 2 | 3 |
|---|---|---|---|
| 2 x 6, Corrugated fin | 24% | 76% | - |
| 3 x 4, Corrugated fin | 6% | 45% | 50% |

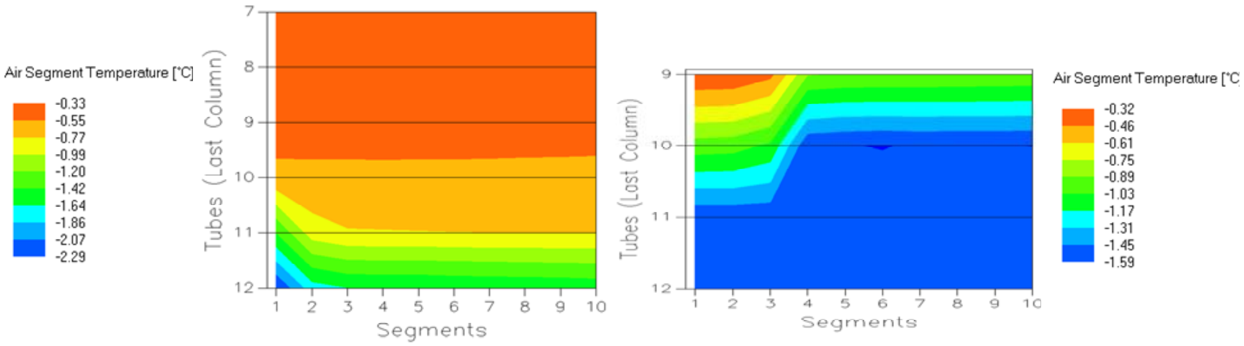
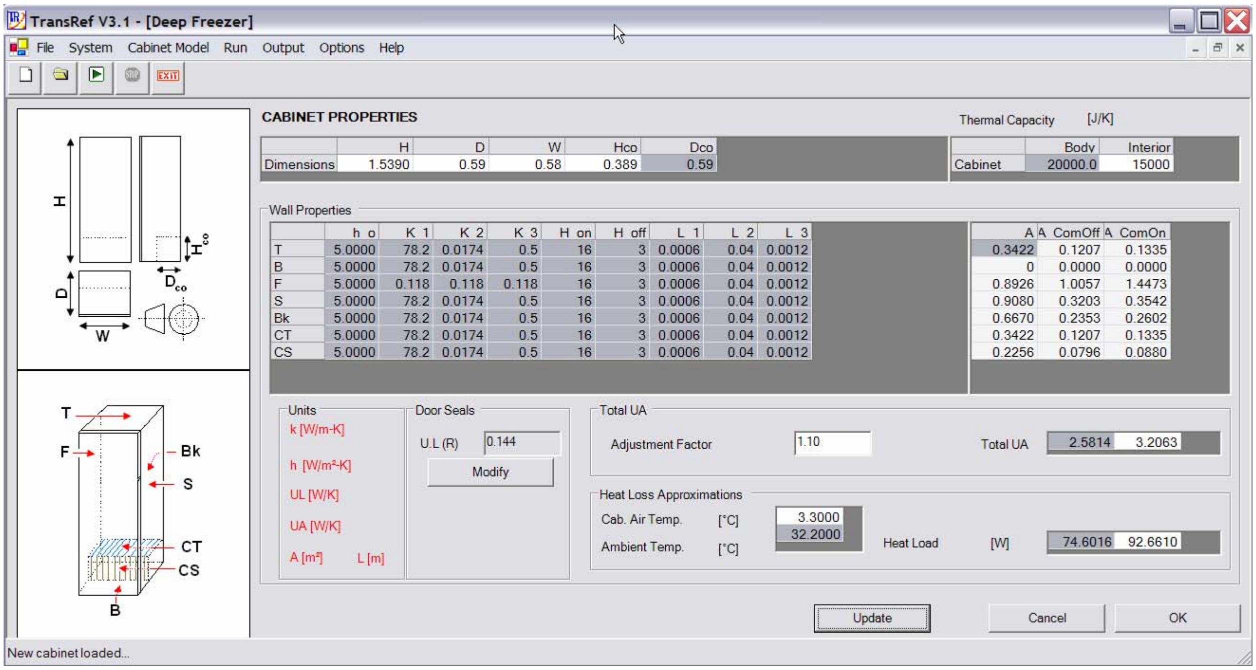


**Figure 5: Air-Side Outlet Temperature Profile**

## SYSTEM PERFORMANCE

To evaluate the applicability of the cycle components designed for medium temperature refrigeration systems, the reach-in-unit having 200 liter effective internal volume was selected and its performance was evaluated. Cooling load of the cabinet was evaluated by using the refrigeration system transient simulation model (CEEE (2), 2005). For the cabinet load evaluation, the cabin average temperature was assumed to be 3.3°C. Results from the simulation are shown in Figure 6 and Table 8. Cabinet loads calculated are 68.0 W, 92.7 W, and 119.3 W at ambient temperature 24.5°C, 32.2°C, and 40.5°C, respectively. When the cabinet loads calculated are compared with the cooling capacity delivered by the $CO_2$ refrigeration system, the cooling capacity of the designed system can provide 75% or greater cooling capacity than required for all ambient temperatures investigated. Therefore, it is concluded the current design of the $CO_2$ refrigeration cycle can provide adequate cooling capacity for a 200 liter cabinet.



CABINET PROPERTIES

| | H | D | W | Hco | Dco |
|---|---|---|---|---|---|
| Dimensions | 1.5390 | 0.59 | 0.58 | 0.389 | 0.59 |

Thermal Capacity [J/K]

| | Body | Interior |
|---|---|---|
| Cabinet | 20000.0 | 15000 |

Wall Properties

| | h o | K 1 | K 2 | K 3 | H on | H off | L 1 | L 2 | L 3 |
|---|---|---|---|---|---|---|---|---|---|
| T | 5.0000 | 78.2 | 0.0174 | 0.5 | 16 | 3 | 0.0006 | 0.04 | 0.0012 |
| B | 5.0000 | 78.2 | 0.0174 | 0.5 | 16 | 3 | 0.0006 | 0.04 | 0.0012 |
| F | 5.0000 | 0.118 | 0.118 | 0.118 | 16 | 3 | 0.0006 | 0.04 | 0.0012 |
| S | 5.0000 | 78.2 | 0.0174 | 0.5 | 16 | 3 | 0.0006 | 0.04 | 0.0012 |
| Bk | 5.0000 | 78.2 | 0.0174 | 0.5 | 16 | 3 | 0.0006 | 0.04 | 0.0012 |
| CT | 5.0000 | 78.2 | 0.0174 | 0.5 | 16 | 3 | 0.0006 | 0.04 | 0.0012 |
| CS | 5.0000 | 78.2 | 0.0174 | 0.5 | 16 | 3 | 0.0006 | 0.04 | 0.0012 |

| A | A ComOff | A ComOn |
|---|---|---|
| 0.3422 | 0.1207 | 0.1335 |
| 0 | 0.0000 | 0.0000 |
| 0.8926 | 1.0057 | 1.4473 |
| 0.9080 | 0.3203 | 0.3542 |
| 0.6670 | 0.2353 | 0.2602 |
| 0.3422 | 0.1207 | 0.1335 |
| 0.2256 | 0.0796 | 0.0880 |

Units
k [W/m-K]
h [W/m²-K]
UL [W/K]
UA [W/K]
A [m²] L [m]

Door Seals
U.L (R) 0.144

Total UA
Adjustment Factor 1.10
Total UA 2.5814 3.2063

Heat Loss Approximations
Cab. Air Temp. [°C] 3.3000
Ambient Temp. [°C] 32.2000
Heat Load [W] 74.6016 92.6610

New cabinet loaded...

**Figure 6: Cabinet Load of Reach-In-Unit at 32.2°C Ambient Temperature**

**Table 8: Comparison of Cabinet Load and Cooling Capacity of Condensing Unit**

| Ambient Temp [°C] | 24.5 | 32.2 | 40.5 |
|---|---|---|---|
| Cabin Temp [°C] | 3.3 | 3.3 | 3.3 |
| Light [W] | 15 | 15 | 15 |
| Cabinet Heat Transfer Load Through Wall [W] | 68.0 | 92.7 | 119.3 |
| Total Cabinet Thermal Load [W] | 83.0 | 107.7 | 134.3 |
| Cooling Capacity [W] | 394 | 305 | 235 |
| Capacity/Load Ratio | 4.75 | 2.83 | 1.75 |

## CONCLUSION

The performance potential of $CO_2$ transcritical cycles with a hermetic linear compressor was simulated for medium temperature refrigeration systems by using measured compressor efficiencies. The simulated results show that the cooling capacity is 235 W at 40.5°C ambient temperature and the COP is 1.31 at 32.2°C ambient temperature. The heat exchangers were designed using the heat exchanger design software. The performance of the $CO_2$ linear compressor together with heat exchangers suitably designed can be successfully applied to medium temperature refrigeration systems having 200 liter effective volume.

### NOMENCLATURE

| | | | |
|---|---|---|---|
| AFR | Air flow rate | COP | Coefficient of Performance |
| HFC | Hydrofluorocarbon | HTC | Heat transfer coefficient |
| P | Pressure | PD | Pressure drop |
| PR | Pressure ratio | T | Temperature |

***Greek letters***

| | |
|---|---|
| $\eta$ | Efficiency |

***Subscripts***

| | | | |
|---|---|---|---|
| comp | compressor | dis | discharge |
| ev | evaporator | gc | gas cooler |
| opt | optimum | ref | refrigerant |
| vol | volumetric | | |

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