Conversion of platelet incubator refrigeration system to R600a and performance optimization

Matej Visek
Creative Thermal Solutions, United States of America, matej.visek@creativethermalsolutions.com

Stefan Elbel
stefan.elbel@creativethermalsolutions.com

Pega Hrnjak
pega.hrnjak@creativethermalsolutions.com

Brian Hoaglan
Helmer Scientific, USA, bhoaglan@helmerinc.com

Chengzhi Tang
Helmer Scientific, USA, ctang@helmerinc.com

See next page for additional authors

Follow this and additional works at: http://docs.lib.purdue.edu/iracc

Visek, Matej; Elbel, Stefan; Hrnjak, Pega; Hoaglan, Brian; Tang, Chengzhi; and Smith, Dennis, "Conversion of platelet incubator refrigeration system to R600a and performance optimization" (2016). International Refrigeration and Air Conditioning Conference. Paper 1814.
http://docs.lib.purdue.edu/iracc/1814

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.
Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at https://engineering.purdue.edu/Herrick/Events/orderlit.html
Authors
Matej Visek, Stefan Elbel, Pega Hrnjak, Brian Hoaglan, Chengzhi Tang, and Dennis Smith
Conversion of platelet incubator refrigeration system to R600a and performance optimization

Matej VISEK\textsuperscript{(1,*)}, Stefan ELBEL\textsuperscript{(1,2)}, Pega HRNJAK\textsuperscript{(1,2)}, Brian HOAGLAN\textsuperscript{(3)}, Chengzhi TANG\textsuperscript{(3)}, Dennis SMITH\textsuperscript{(3)}

\textsuperscript{1}Creative Thermal Solutions, Inc.
2209 North Willow Road, Urbana, IL 61802, USA

\textsuperscript{2}University of Illinois at Urbana-Champaign
Department of Mechanical Science and Engineering
1206 West Green Street, Urbana, IL 61801, USA

\textsuperscript{3}Helmer Scientific, Inc.
14400 Bergen Boulevard, Noblesville, IN 46060, USA

* Corresponding Author Email: matej.visek@creativethermalsolutions.com

ABSTRACT

Platelet incubators are refrigerated laboratory storage devices aimed at preserving platelets in liquid form at close to ambient temperature. Quality and shelf life of the stored platelets strongly depend on the storage temperature uniformity and continuous movement of the platelets provided by an agitator to avoid coagulation. Incubator manufacturers usually provide assurance that temperature uniformity will be within +/-1°C from the set point. Such strict requirement of uniformity is achieved by continuously running a forced convection vapor compression refrigeration system and by balancing excess cooling capacity with a controlled pulse heater located inside the cabinet. Dominant refrigerants currently employed in refrigerated laboratory equipment are HFCs with high GWP. In the future, HFCs will be gradually replaced mostly by flammable natural refrigerants of the ASHRAE A3 group such as R600a (isobutane), R290 (propane) and R170 (ethane) depending on the cooler size and application temperature. Flammable refrigerant charges are limited to 150g or less which in some cases requires complete redesign of the refrigeration circuit.

The focus of this study was to convert the refrigeration system of a platelet incubator to hydrocarbon refrigerant. The selected incubator is able to store 32 apheresis bags and based on the required cooling capacity R600a refrigerant was identified as most suitable replacement for R134a. The baseline R134a system performance was experimentally evaluated across the range of ambient temperatures allowed by the manufacturer, from 15°C to 35°C and at 3 different cabinet set points 20°C, 22°C and 27°C. Attention was given to the energy consumption by distinguishing between contributions of individual components (compressor, fans, pulse heater, agitator, condensate tray heater and controller). Temperature uniformity was determined from measurements at 17 locations inside the cabinet over a 24 hour period. Afterwards, the refrigeration system was converted to R600a refrigerant and its performance was optimized by capillary tube size selection, refrigerant charge amount, evaporator fan speed and by replacing the condensate heater with a discharge gas loop. The redesigned machine required only 50g of R600a refrigerant charge, an average 20% lower energy consumption, cabinet temperature uniformity within the required +/-1°C for all tested conditions, and uniformity of +/-0.5°C at 15°C and 25°C ambient temperatures.
1. INTRODUCTION

Worldwide intention to phase out HFCs with high GWP is forcing even manufactures of medical and pharmaceutical refrigeration equipment to explore low GWP refrigerant alternatives. The most important criteria for selection of medical equipment is reliability and fast serviceability, thus this industry is very slowly responding to the efforts for reducing global warming foot print. In Europe hydrocarbon refrigerants are widely accepted in household refrigerators and in the beverage cooling industry and even medical and pharmaceutical manufacturers are sometimes offering their “green” natural refrigerant alternatives. One of the reasons for the slower response in the US is the limited experience of servicing personnel with flammable refrigerants. However, also in US the servicing personnel is rapidly gaining practice as many US light commercial equipment manufacturers already sell and manufacture refrigeration equipment with natural refrigerants (Tamasiunaite, 2016).

However, the use of hydrocarbon refrigerants is well established in some parts of the world, and there are many recent papers demonstrating advantages of hydrocarbons over HFC refrigerants in many fields of the refrigeration industry. In domestic refrigeration mixtures of propane and isobutane were investigated as replacement to R134a by Wongwises and Chimares (2005) and Yu and Teng (2014). Zhou and Zhang (2010) retrofitted an R22 residential split type air-conditioner with R290. Peixoto et al. (2000) studied the performance of a commercial freezer working with isobutane. Elefsen et al. (2003) worked on R290 ice cream freezers and Danfoss (2010) presented a development of components for commercial R290 ice makers. Fuentes et al. (2014) showed that even very large beverage coolers holding up to 700 cans can be converted to propane with proper design of the refrigeration system and still meet all the requirements including less than 150g of refrigerant charge. All these studies demonstrate, in addition to using low GWP refrigerants, positive single sometimes doubled digit improvements in the energy consumption after conversion of the baseline system to the hydrocarbon refrigerant.

This paper shows an approach in the conversion of a countertop platelet incubator refrigeration system from R134a to hydrocarbon refrigerant and its experimental performance validation. Based on the capacity and operating conditions, isobutane refrigerant (R600a) was selected as drop-in replacement with compressor exchange and very small refrigeration system changes to obtain improved functionality and performance of the system. The converted unit with hydrocarbon refrigerant has to have less than 150g of charge to comply with government standards. The necessary changes needed for the unit to meet all relevant safety standard related to hydrocarbon were not part of this study.

2. PRINCIPLE OF OPERATION, PERFORMANCE REQUIREMENTS AND DESIGN CHALLENGES

2.1 Platelet incubator principle of operation

A commercially available PC1200h platelet incubator utilizing 142g of R134a refrigerant was selected as a baseline for the conversion to the hydrocarbon refrigerant. Compared to standard compressor cycling refrigerators and air-conditioning units the incubator’s principle of operation is different. The refrigeration system runs continuously and a cabinet air heater located in the outgoing air stream from the evaporator is used to precisely adjust the desired temperature of the cabinet. This type of operation as seen in Figure 1 is very similar to calorimetric rooms or thermostatic baths where elevated temperature uniformity and stability are required.

Figure 1: PC1200h incubator with agitator and schematic of operating principle
Obviously, running the refrigeration system continuously leads to significantly higher energy consumption compared to a compressor cycling systems. The excess cooling capacity at any condition has to be balanced by additional heater power. To minimize the energy consumption it is very important to correctly match cooling capacity of the refrigeration system and heater power. The system cooling capacity needs to be high enough to reach the lowest set point at the highest ambient temperature. The heater power has to be high enough to reach the highest set point at the lowest ambient temperature with the refrigeration system running. These two extreme conditions are the corner points of the test matrix outlined in Figure 2.

<table>
<thead>
<tr>
<th>Ambient temperature °C</th>
<th>Cabinet set point °C</th>
<th>Test point significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>20</td>
<td>Lowest evaporation temperature</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>Maximal heater power</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>Rating condition for energy consumption</td>
</tr>
<tr>
<td>35</td>
<td>35</td>
<td>Maximal cooling capacity needed</td>
</tr>
</tbody>
</table>

![Figure 2: PC1200h incubator test matrix with explanation of test point significance](image)

### 2.2 Performance requirements

General requirements for the storage temperature of platelets in liquid form are described in the current 30th edition of AABB Standards for Blood Banks and Transfusions Services (2016). The required platelet temperature is between 20°C and 24°C providing continuous gentle agitation. This results in a range of +/- 2°C from the 22°C set point. As the lifesaving and financial value of the platelets is significant most of storage equipment manufactures tend to be on the safe side and design their equipment to meet at least 22°C +/- 1°C cabinet air temperature. The air uniformity and stability is assessed by actual 24 hours experimental measurement with 17 weighted thermocouples distributed throughout the cabinet. The cabinet temperature uniformity is determined by following equation:

\[
\text{Max} \left( \int_{t_0}^{t_1}(T_i)\,dt \right) \cdot t - \text{Min} \left( \int_{t_0}^{t_1}(T_i)\,dt \right) = dT_{\text{uniformity}}
\]

Where:  
- \( T_i \) – temperature of i-th thermocouple out of 17 weighted thermocouples  
- \( t \) – actual test duration – 24 hours  
- \( dT_{\text{uniformity}} \) – cabinet temperature uniformity

Gentle agitation of the platelets is achieved by a separate piece of equipment called an agitator as shown in the left part of Figure 1. It is inserted into the incubator and powered through an internal outlet. The agitator’s motor and fan generate additional heat in the cabinet and increase the load to the refrigeration system. This can also impact cabinet air temperature uniformity by locally producing too much heat. The incubator used in this study, a PC1200h, was designed to operate at ambient temperatures between 15°C and 35°C and set points between 20°C and 35°C. As mentioned earlier, the platelets require temperatures between 20°C and 24°C. The majority of incubators are operated with a 22°C set point and are located in air-conditioned laboratories. In some specific cases, such as for research purposes, slightly higher set points approximately 27°C can be required even for platelets. Any higher set points are for specialty applications usually not involving platelet storage. In order to focus the application on the platelet it was decided that the test matrix outlined in the Figure 2 should cover all the ambient temperatures between 15°C and 35°C and set points between 20°C and 27°C. To verify the functionality of the condensate heater and later of the discharge gas loop the system was run at 24°C ambient temperature, 18°C dew point and 22°C cabinet set point.
2.3 Design challenges in incubator conversion to hydrocarbons

Table 1 compares thermophysical properties of 3 working fluids; baseline R134a and 2 potential replacement hydrocarbon refrigerants R600a (isobutane) and R290 (propane). REFPROP software (Lemmon et al., 2013) was used for the evaluation of the properties at the operating condition; 10°C evaporation, 55°C condensation, 3K sub-cooling and 10K superheat temperature.

<table>
<thead>
<tr>
<th>Line #</th>
<th>Refrigerant</th>
<th>R134a</th>
<th>R600a</th>
<th>R290</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Name</td>
<td>1,1,1,2-Tetra-fluoro-ethane</td>
<td>isobutane</td>
<td>propane</td>
</tr>
<tr>
<td>2</td>
<td>Pressure at 55°C</td>
<td>kPa</td>
<td>1492</td>
<td>773</td>
</tr>
<tr>
<td>3</td>
<td>Pressure at 10°C</td>
<td>kPa</td>
<td>415</td>
<td>221</td>
</tr>
<tr>
<td>4</td>
<td>Liquid density at 55°C</td>
<td>kg/m³</td>
<td>1094</td>
<td>515</td>
</tr>
<tr>
<td>5</td>
<td>Density ratio HC/R134a</td>
<td>-</td>
<td>47%</td>
<td>41%</td>
</tr>
<tr>
<td>6</td>
<td>System charge (estimation)</td>
<td>g</td>
<td>142</td>
<td>67</td>
</tr>
<tr>
<td>7</td>
<td>Volumetric capacity</td>
<td>kJ/m³</td>
<td>2668</td>
<td>1446</td>
</tr>
<tr>
<td>8</td>
<td>Volumetric capacity ratio</td>
<td>-</td>
<td>100%</td>
<td>185%</td>
</tr>
<tr>
<td>9</td>
<td>Compressor displacement (same capacity)</td>
<td>cm³</td>
<td>4.5</td>
<td>8.3</td>
</tr>
<tr>
<td>10</td>
<td>Fluid ideal COP 10/55/20°C &amp; 3K SC</td>
<td>-</td>
<td>4.95</td>
<td>5.15</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>100%</td>
<td>104%</td>
<td>98%</td>
</tr>
<tr>
<td>12</td>
<td>Vapor velocity in suction line 3/8&quot;</td>
<td>m/s</td>
<td>1.72</td>
<td>3.18</td>
</tr>
<tr>
<td>13</td>
<td>Pressure drop in 1 m of suction line</td>
<td>Pa</td>
<td>67</td>
<td>69</td>
</tr>
<tr>
<td>14</td>
<td>Liquid velocity in liquid line 1/4&quot;</td>
<td>m/s</td>
<td>0.05</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Isobutane operation pressure is roughly half of the R134a pressure and that of propane is slightly higher as shown in Table 1 rows 2 and 3. Thus for a propane application it is necessary to make sure the burst pressure of the components is sufficiently high to cover the increased working pressure. Assuming the components were properly designed for R134a they can be used with R600a without any further investigation.

Hydrocarbon system refrigerant charge of light commercial applications is currently limited to 150g. The refrigerant charge of the existing incubator is 142g of R134a. For the hydrocarbon charge estimation the same volume of liquid is assumed. By using the liquid density ratio shown in row 5 of Table 1, the hydrocarbon charge amount is estimated to be 47% (67g) and 41% (58g) of the current refrigerant charge for isobutane and propane, respectively. These charge estimates do not account for different solubility of refrigerants in the compressor oil and refrigerant void fractions and heat transfer coefficients in the heat exchangers. Refrigeration oils such as POE are well known for absorbing a large quantity of hydrocarbon refrigerant, thereby increasing the required charge amount.

Isobutane has a much lower volumetric capacity compared to R134a as shown in Table 1, row 7. Thus, to achieve same system cooling capacity the R600a compressor displacement needs to be approximately 85% higher than for the R134a compressor (assuming identical compressor speed). The opposite is valid for propane for which the compressor displacement has to be 23% lower than that of R134a. In addition, the hydrocarbon compressor has to be able to operate reliably without the compressor tripping at high back pressure conditions. After summarizing available propane and isobutane compressors on the market it was found that high back pressure compressors for the required capacity are only available for R600a refrigerant and only for 100V and 220V 50Hz power supply.
Comparing the ideal refrigeration cycle COP for these 3 refrigerants, R600a is the most efficient followed by R134a and propane with very small differences as shown in Table 1, rows10 and 11. On the other hand, R600a’s lower vapor density leads to higher velocity in the suction pipe as shown in Table 1, row12. The higher velocity is beneficial for oil return from the evaporator to the compressor, higher heat transfer, but can also cause higher pressure drop and reduce cycle efficiency. In Table 1, row 13, pressure drop using the Darcy-Weisbach equation was calculated. The pressure drop for 1 m of suction pipe is very small for all three refrigerants and its effect on the cycle COP can be neglected in short suction pipes found in the incubator. Though it’s important to mention that the same pressure drop can have significantly higher impact on the efficiency of an isobutane cycle compared to R134a or propane, because of the lower operating pressures. Thus, it is vital to perform this calculation for a specific system design in order to identify any requirements to resize refrigeration lines.

Another task in conversion of the incubator is to adjust the capillary tube and refrigerant charge in the way to avoid evaporation temperatures below freezing at any operating condition to avoid frost problems. It is expected that the lowest evaporation temperature is observed at the corner point of lowest ambient temperature and lowest cabinet set point shown in Figure 2.

3. BASELINE TESTING AND COMPONENTS SELECTION

3.1 Incubator instrumentation

The baseline incubator was equipped with T-type thermocouples according to the schematic shown in Figure 3. The thermocouples measuring refrigerant temperature were mounted to the surface of the tubes with a layer of insulation covering them. Air temperatures across the evaporator, condenser and ambient air temperature were measured with thermocouples. 17 thermocouples weighted with brass cylinders (14 mm in diameter and 20 mm height) were located at the shelves of the agitator to measure air temperature uniformity. The thermocouples were all calibrated with SPRT achieving +/-0.2°C measurement accuracy at the required temperature range from 19°C to 28°C. Chamber humidity was recorded by a chilled mirror hygrometer. The Incubator’s power was measured by two power transducers. The first one was used to record power of the cabinet heater and the second one for measuring power consumption of all other components. In addition, the converted incubator was instrumented with two pressure transducers located on the compressor suction and discharge to help with diagnosis and adjustment of the system charge and capillary tube. The instruments with corresponding accuracies are summarized in Table 2.

<table>
<thead>
<tr>
<th>Value measured</th>
<th>Instrument</th>
<th>Manufacturer</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>T-type thermocouple</td>
<td>Omega</td>
<td>+/-0.2°C in the range 19°C to 28°C after calibration</td>
</tr>
<tr>
<td>Power</td>
<td>power transducer</td>
<td>OhioSemitronics</td>
<td>+/-0.5% F.S.</td>
</tr>
<tr>
<td>Dew point</td>
<td>chilled mirror sensor</td>
<td>General Eastern</td>
<td>+/-0.36°C</td>
</tr>
<tr>
<td>Pressure</td>
<td>pressure transducer</td>
<td>Sensotec</td>
<td>+/-0.05% F.S.</td>
</tr>
</tbody>
</table>

Figure 3: Schematic of incubator refrigeration circuit with instrumentation
3.2 Baseline performance testing

The incubators are manufactured for various voltages and frequencies ranging from 100V 50Hz/60Hz for the Japanese market, 120V 60Hz for North America, 220V 60Hz for South America and 220V 50Hz for European countries. During the baseline testing both 120V 60Hz and 220V 50Hz models were measured. However, in this paper is focused on the 220V 50Hz model as the hydrocarbon high back pressure compressors for the desired capacity range are currently only available for this power option.

The PC1200h was experimentally tested at the conditions outlined in the test matrix shown in Figure 2. Temperatures and power were recorded for 24 hours in 2s intervals. Energy consumption reported in kWh/day was evaluated as the integral of the measured power over 24 hours test duration and temperature uniformity was calculated according to equation (1). In addition, power of each energy consuming component was measured separately beforehand in order to determine its individual contribution to the overall energy consumption. A summary of the baseline energy consumption results is reported in Figure 4.

![Figure 4: Baseline R134a incubator energy consumption results](image)

The baseline unit performed very well at low and medium ambient temperatures, where the cabinet temperature uniformity was fully within the required specification of +/-1°C from the set point as shown in Figure 5, even without the manufacturer recommended cabinet probe offset recalibration. However, at high ambient temperature the incubator was just slightly short of cooling capacity to reach the lowest set point at the highest ambient temperature which is possible to see from the cabinet heater power reading in Figure 4. Looking closer at the measured data it was identified that the system didn’t have any sub-cooling and two-phase refrigerant was expanding through the capillary tube. The evaporator was flooded with liquid refrigerant, thus a slightly more restrictive capillary tube would help in reaching the corner point of the test matrix for the baseline system.

![Figure 5: Baseline R134a cabinet temperature uniformity results](image)
3.3 Modifications of hydrocarbon incubator

The compressor size was selected according to the existing R134a compressor cooling capacity. The current R134a compressor with 4.49cm³ proved to have sufficient cooling capacity even for the largest incubator PC4200h. Thus, one condensing unit design can be used across all sizes of the incubators leading to fewer parts and simpler manufacturing.

Based on the volumetric capacity calculation reported in Table 1, rows 7-9 the new isobutane compressor should have a displacement 8.3cm³. However, the new generation of isobutane compressors offers higher volumetric efficiency, thus the same cooling capacity can be reached with lower displacement. The EMU5132Y with 6.76cm³ displacement was identified as the closest match to the baseline cooling capacity. The R600a compressor’s COP is almost 50% higher compared to the baseline R134a, thus significant energy saving is expected. Both cooling capacity and COP at 55°C condensing temperature are shown in Figure 6. The amount of compressor oil decreased from 303ml to 180ml when moving to the new hydrocarbon compressor. This has positive impact on lowering the amount of isobutane refrigerant charge needed.

![Graph showing comparison of R134a and R600a compressors](image)

**Figure 6:** Comparison of R134a baseline and selected R600a compressors at 55°C condensing temperature

The baseline uniformity results showed slightly higher cabinet uniformity at high ambient temperature conditions. Therefore, the evaporator fan motor speed was increased to 2000RPM with the same fan blade in order to increase the air flow rate without requiring any other changes to the shroud or other internal components of the incubator.

The compressor discharge line was routed down to the drip pan and ultimately replaced the electric condensate heater. It eliminated 54W of the continuously powered condensate heater and saved 1.3kWh/day at all operating conditions. The proper functionality of discharge gas loop was verified by running the incubator at 24°C ambient temperature, 18°C dew point and 22°C cabinet set point.

4. PERFORMANCE RESULTS OF CONVERTED INCUBATOR TO R600A

After implementation of all the changes outlined above to the baseline incubator the unit went through several rounds of testing to optimize isobutane charge amount and dual capillary tube length at the condition in the lower left corner of the test matrix. Both capillary tubes had to be shorten by 430mm to provide less pressure drop for R600a refrigerant. The optimum refrigerant charge was determined to be 50g. Figure 7 demonstrates how important the accuracy in charging the isobutane refrigeration system is. The refrigerant charge was increased by 3g followed by an additional 2g and the incubator lost all the excess cooling capacity and even didn’t reach the required operating condition anymore.
Figure 7: Impact of R600a charge amount on the system performance (overcharging with 3g and 5g)

The properly charged converted incubator system with 50g of R600a was tested at all the test matrix conditions. The system had 57W of excess cooling capacity at highest ambient temperature and lowest cabinet set point. The capillary tube and charge were optimized on purpose to have some extra capacity at the corner point. It was shown that even small variation in the refrigerant charge amount could cause the incubator not to reach the corner point. The excess capacity causes slightly higher energy consumption but assures proper functionality of the incubator. The energy consumption results are shown in Figure 8 and are compared to the R134a baseline system. On average 20% lower energy consumption was achieved with conversion of the incubator to the isobutane refrigerant. Approximately 10% comes from eliminating the electric condensate heater and the remainder of the savings are achieved by higher compressor efficiency.

Figure 8: Comparison of energy consumption between R134a baseline and R600a incubator
The cabinet temperature uniformity was improved in the converted incubator unit compared to baseline R134a unit and the results are shown in Figure 9. Uniformity is well within +/-1°C required by the manufacturer. At low and medium ambient temperature the uniformity is even better than +/-0.5°C.

Figure 9: Cabinet temperature uniformity of R600a incubator

5. CONCLUSIONS

The paper summarized the approach of converting an existing R134a platelet incubator to low GWP hydrocarbon refrigerant R600a. It was demonstrated that the system can be converted to this natural refrigerant with minimum changes of the R134a system. The conversion was also an opportunity to adjust and improve the functionality of the system with only mild changes and modifications. The main conclusions are summarized below:

- It is possible to convert even specialty medical equipment such as platelet incubators to low GWP hydrocarbon refrigerant with minimum system changes without compromising its functionality or reliability
- Compressor, capillary tube adjustment and refrigerant charge amount were the necessary changes of the system
- Small capacity high back pressure compressors are currently available only for R600a as 50Hz versions
- R600a compressors are significantly more efficient than R134a models for this application
- The incubator functionality and cabinet temperature uniformity was improved during conversion and on average 20% of energy was saved compared to the R134a baseline system
- Accuracy of charging equipment needs to be assured during production to achieve performance repeatability and incubator reliability

NOMENCLATURE

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>AABB</td>
<td>American Association of Blood Banks</td>
<td>AABB</td>
</tr>
<tr>
<td>AMB</td>
<td>ambient</td>
<td>AMB</td>
</tr>
<tr>
<td>COP</td>
<td>coefficient of performance (-)</td>
<td>COP</td>
</tr>
<tr>
<td>GWP</td>
<td>global warming potential</td>
<td>GWP</td>
</tr>
<tr>
<td>HFC</td>
<td>hydrofluorocarbon</td>
<td>HFC</td>
</tr>
<tr>
<td>HC</td>
<td>hydrocarbon</td>
<td>HC</td>
</tr>
<tr>
<td>IHX</td>
<td>suction line heat exchanger</td>
<td>IHX</td>
</tr>
</tbody>
</table>
| SPRT         | standard platinum resistance thermometer | SPRT | POE polyolester oil
|              |                                    | SC      |
|              |                                    | SP      |
|              |                                    | t       |
|              |                                    | T       |

16th International Refrigeration and Air Conditioning Conference at Purdue, July 11-14, 2016
Subscripts
- a: air
- c: condenser
- cp: compressor
- e: evaporator
- i: in
- o: out
- r: refrigerant
- x: expansion

ACKNOWLEDGEMENT

The incubator conversion study to hydrocarbon refrigerant was accomplished with generous help from Helmer Scientific.

REFERENCES


