A study on the use of propane (R-290) in vending machines as a substitute for R-134a to minimise the global warming potential

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Abstract: The refrigerant R-134a is widely used in vending machines, and it is a greenhouse gas with high global warming potential. The United States Environmental Protection Agency has mandated that R-134a be replaced with an environmentally friendly refrigerant. In this study, we compared the performance and safety of R-290 as a substitute for R-134a in vending machines. We compared the two refrigerants in a vending machine equipped with a single-stage compressor, four thermocouples, and a data log recorder. Our results demonstrate that R-290 performs as well as R-134a; in addition, it uses 31.4% less energy and 60% less refrigerant. The evaporator and condenser temperatures for R-290 were comparable to those for R-134a. Therefore, we conclude that R-290 is an excellent replacement for R-134a. In addition, R-134a’s global warming potential is 1300, while R-290’s global warming potential is 3, and its ozone depletion potential is zero. Finally, R-290 can be used safely and complies with Underwriter Laboratory® safety standards.

Keywords: global warming potential; GWP; greenhouse gas; R-134a refrigerant; propane (R-290) refrigerant; vending machines.


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1 Introduction

Ozone (O₃) is a gas that is naturally present in the stratosphere. It forms the ozone layer approximately 50 kilometres above the Earth’s surface, which prevents harmful ultraviolet (UV) radiation from reaching the Earth’s surface. UV radiation can cause a wide range of health problems in humans, including skin cancer, eye damage, and immune system suppression. UV radiation can also harm sensitive crops such as soybeans and reduce crop production (De Grujil et al., 2003).

1.1 Literature review

In 1974, scientists discovered that stratospheric ozone was being destroyed by a group of manufactured chemicals containing chlorine and/or bromine, which are referred to as ozone-depleting substances (ODS) (Molina and Rowland, 1974). The chlorofluorocarbons (CFCs) and hydro-chlorofluorocarbons (HCFCs) in refrigerants were a major factor in ozone layer depletion, accounting for over 80% of the total stratospheric ozone destruction (Hipara, 2013).

By 1987, increased scientific awareness of the causes of ozone depletion compelled many countries to sign the Montreal Protocol. These countries agreed to take steps to reduce and eliminate ODS and protect the ozone layer for the safety of humans and the environment (Benedick, 1991). The protocol was implemented in the USA under the Clean Air Act (CAA) via amendments in 1990 and 1998 that mandated a gradual end to the production of ODS (US EPA, 2014a).

As a result of the Montreal Protocol, hydrofluorocarbons (HFCs) replaced CFCs and HCFCs in refrigerants. HFCs do not contain chlorine and therefore do not deplete the ozone layer, so the Montreal Protocol did not restrict their use. However, HFCs are greenhouse gases and have a high global warming potential (GWP). The GWP is the total energy absorbed by a gas over a certain period of time compared to carbon dioxide (US EPA, 2014b). HFCs are capable of trapping up to a thousand times more heat than carbon dioxide in the atmosphere (Bose, 2012).

In total, more than 2.6 million refrigerated vending machines are in use, cooling fresh food and soft drinks in buildings and public areas. These machines mainly use HFC refrigerants, which have a high environmental impact because of their GWP (Cadmus Group, 2009). HFC emissions are projected to grow by approximately 140% between 2005 and 2020 because of increasing demand for refrigeration (US EPA, 2015).

The US Environmental Protection Agency (EPA) has continued to develop regulations to encourage the use of refrigerants that are environmentally friendly and
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Protect public health without harming the ozone layer. Under the Significant New Alternatives Policy (SNAP) program, the EPA proposed changing the status of certain HFCs from acceptable to unacceptable for various end uses in the refrigeration and air conditioning sectors. The new rule took effect on January 1, 2016 (US EPA, 2014b). The greatest impact of this change is the phase-out of the HFC R-134a, which is widely used in automobile and vending machine refrigeration units.

Yamasaki et al. (2004) performed two laboratory experiments and field tests on two different Coca-Cola® vending machines; the first used a carbon dioxide (CO₂) refrigeration cycle, and the second used an R-134a refrigeration cycle. Both vending machines had the same fan, insulation and heat exchanger sizes, but because the CO₂ cycle operates at a higher pressure, a Sanyo® two-stage rolling piston compressor with thicker tubing was used in that unit. The results showed that the vending machine with CO₂ refrigerant used 17% less energy than the machine with R-134a. The authors concluded that CO₂-based equipment was more reliable and more energy efficient than equivalent R-134a-based equipment.

Another study examined vending machines that used CO₂ rather than R-134a as a refrigerant by conducting laboratory and field tests using a Danfoss® compressor. The results demonstrated energy improvements of 18% to 37% for CO₂ vending machines compared to the R-134a machines, depending on the application and ambient conditions (Veje and Süss, 2004).

CO₂ vending machines operate with five times greater pressure than machines using R-134a. Therefore, CO₂ machines require a two-stage compressor with thicker tubes and better sealing. This increases the cost of the vending machines’ refrigeration units and reduces their competitive advantage in the marketplace compared to R-134a vending machines, which only need a one-stage compressor with standard thickness tubes and sealing.

A study in Europe compared the energy efficiency of propane (R-290) versus R-134a in a bottle cooler. The results showed that the R-290 system reduced power consumption by 35% at the same service rate (Bel, 2005). This outcome encouraged us to investigate the applicability of R-290 in vending machines. While bottle coolers have a similar refrigeration cycle, they differ from typical vending machines because they have an insulated glass door that releases a large amount of cooled air every time it is opened. This feature lowers the cooling capacity and makes it difficult to control the interior temperature, while vending machines have a closed cabinet and dispense a single bottle at a time.

1.2 Objective

Many properties of a refrigerant must be considered when choosing the appropriate working fluid for a particular application. Most characteristics include the ozone depletion potential (ODP), GWP, safety level, system material compatibility, and lubricants needed in the system. The primary objective of this study was to evaluate the safety and feasibility of using propane (R-290) as the refrigerant in a vending machine instead of R-134a. We also tested the conformity and reliability of a refrigeration unit charged with propane. Our aim was to find a new refrigerant with an acceptable GWP and no ODP that would meet the new EPA refrigerant requirements.
2 Methodology

To determine the efficiency of a propane (R-290) refrigeration system, it was necessary to first collect baseline data on R-134a refrigeration cycles. In this study, we tested a standard commercial vending machine equipped with a Danfoss® 3165.1 KJ cooling capacity single-stage compressor charged with 400 grams of R-134a, in accordance with SECOP GmbH (2013). Four K-type thermocouples (T) and a data log recorder were used for temperature measurements.

The thermocouples were setup in two configurations. In the first configuration, thermocouples were placed in four different locations to ensure that the entire cabinet was cooled to an appropriate level (4.5°C). The thermocouples were arranged as follows: T1 was located in the back of the unit at the top; T2 in the front of the unit at the top; T3 in the front at the bottom; and T4 in the back at the bottom. The location of T4 allows it to measure the evaporator output temperature (see Figure 1). In the second configuration, the thermocouples were placed at the inlets and outlets of the condenser and evaporator. The thermocouples were placed in the vending machine cabinet to measure the performance and uniformity of cooling throughout the vending machine’s product area. Placing thermocouples in the evaporator and condenser of the refrigeration unit allowed us to compare the cooling performance of the refrigeration units with R-134a versus R-290.

Figure 1  Cut-away view of the inside of the vending machine cabinet (see online version for colours)

A series of tests were conducted over a six-month period. The vending machine was left running for 36 hours during each test. The vending machine and its contents were allowed to warm to room temperature before the refrigeration unit was started to see how
long the unit would take to reach a steady state temperature. The power meter was connected through the vending machine’s power cord to collect electrical usage data.

After establishing baseline experimental data for R-134a, the refrigerant was removed from the vending machine refrigeration system and replaced with 150 g of R-290, in accordance with SECOP GmbH (2013). The lubricants were not changed. The thermocouples were inserted at the same points in the vending machine as for the R-134a testing and a power meter was used to collect electrical usage data.

The vending machine was filled with water and soda bottles. It was left running for 36 hours. In addition to the thermocouples, an infrared camera (FLIR®) was used to check the temperature distribution inside the vending machine cabinet.

3 Results

3.1 R-134a results

Because the fully loaded vending machine was initially turned off, it took approximately three and half hours for the first refrigeration cycle to cool the cabinet to 4.5°C. After this initial cool down period, the cooling cycle time was reduced to approximately 37 minutes. The thermocouple measurements show that T1 through T3 all approached steady state values nearing the target temperature of 4.5°C (see Figure 2).

Figure 2 Cabin temperature profiles for the vending machine with R-134a (see online version for colours)

The second thermocouple configuration shows the temperature of the inlets and outlets for the condenser and evaporator (see Figure 3).

After turning the compressor on for three and half hours to reach steady state operation, the peak power use was 400 Watts and the unit consumed 0.188 KW-hr (see Figure 4).
The experiment with R-134a confirmed that the current system worked as expected. It also provided a baseline against which to compare the cooling times and overall cabinet temperatures of the propane system.
3.2 Propane results

After replacing R-134a with propane (R-290), the vending machine was operated for 36 hours again. Because the vending machine was initially turned off, it took two hours for the first refrigeration cycle to cool the cabinet to 4.5°C. After this, the cooling cycle time was approximately 37 minutes. The thermocouple measurements showed that T1 through T3 all approached steady state values with a target temperature of 4.5°C (see Figure 5).

Figure 5  Internal cabin temperature of the R-290 vending machine (see online version for colours)

Figure 6  Inlet and outlet temperature data for the condenser and evaporator of the R-290 vending machine (see online version for colours)
The experiment was repeated with the second thermocouple configuration to measure the temperature at the inlets and outlets of the condenser and evaporator. The temperature profiles are shown in Figure 6.

After turning the compressor on for two hours to reach steady state operation, the constant power draw and accumulated Watt-hours were recorded. The peak power use was 275 W and the vending machine energy consumed 0.129 KW-hr (Figure 7).

**Figure 7** Electrical power usage data for the R-290 refrigeration cycle (see online version for colours)

![Power usage data for R-290 refrigeration cycle](image)

The thermal imaging (infrared) camera was used to verify that the bottled drinks in the vending machine indeed reached the required temperature of 40°F (Figure 8).

**Figure 8** Temperature distribution inside the R-290 vending machine (see online version for colours)

![Temperature distribution inside the R-290 vending machine](image)
4 Discussion

The tests conducted using R-134a refrigerant established baseline requirements for the performance of any substitute refrigerant. The unit with R-134a kept the machine and its bottled drinks at 4.5°C, as required for the customer. The refrigeration system drew 400 Watts of power once the temperature in the machine reached 4.5°C. All tests produced similar results for the R-134a refrigerant.

In this study, the R-134a was removed from the vending machine refrigerant system and replaced with 150 g of propane (R-290). R-134a, which is currently used in millions of vending machines in North America and elsewhere, has a GWP of 1300. In contrast, R-290 has a GWP of 3 and an ODP of zero (Kaltschmitt et al., 2007).

Pittam and Pilcher (1972) showed that the higher enthalpy of propane at a similar operating pressure allows for the use of 60% less refrigerant. The system with propane was operated for several days starting from a room temperature of 18.5°C. It required less time to come to a steady state operating temperature of 4.5°C, and its cycling to maintain that temperature was similar to that of the system with R-134a. Infrared imaging (Figure 8) of the vending machine cabinet with the R-290 refrigerant confirmed that all the drinks in the cabinet reached the required 4.5°C temperature.

The evaporator and condenser temperatures of the system with R-290 were similar to the system with R-134a. The R-134a system uses polyester oil as a lubricant, which is miscible and soluble in the refrigerant. Propane (R-290) is also compatible with this lubricant oil. This means that R-290 can be substituted for R-134a with no change in lubricant.

Our results showed that the difference in power consumption between the systems was significant. The system with R-290 used 31.4% less power than the R-134a system; it also required 43% less time to reach steady state operation. The energy savings of the R-290 over the R-134a amount to approximately 675 KWH per year per vending machine. At a CO₂ reduction of $6.89551 \times 10^{-4}$ metric tons per KWH, the reduction per vending machine per year would be 0.47 metric tons per year (US EPA, 2010). Therefore, the environmental effects of replacing R-134a with R-290 for millions of vending machines in use today would be very significant.

The disadvantage of propane is that it is flammable. When the concentration of propane reaches 2% to 10%, combustion can occur in air (Hildebrand and Noll, 2007). Because propane is flammable, it must be shielded from electrical sparks to prevent explosions in the event that leaks occur. This can be accomplished by sealing the electrical contacts and relays. Proper warnings would also have to be posted on refrigeration equipment, stating that propane is used as a refrigerant in the system. An explosive gas alarm should be installed to detect any gas leaks. These safety issues can be addressed without major expense or modification to existing refrigeration systems. In addition, combustion would probably result from a scenario involving a large or catastrophic leak; it is unlikely for small or slow leaks in the system. Given the relatively small amount of propane in the vending machine (150 g), large leaks are improbable.

Underwriters Laboratories® – UL (2013) sets the standards for the safe use of propane in vending machines in the United States and covers the requirements listed above. They are included in the UL-541 standard.
This study showed that R-290 performs as well as R-134a in a vending machine. It uses less energy and less refrigerant, and necessitates only minimal changes to the refrigerant system to maintain safety requirements.

5 Conclusions

This study clearly demonstrates the advantages of using propane as a substitute for R-134a. The GWP drops from 1300 for R-134a to 3 for R-290, and the ODP of R-290 is zero.

Another advantage of using R-290 is that it would reduce the amount of refrigerant by 60%. Additionally, propane is less expensive than R-134a and other refrigerants, and it is directly compatible as a replacement. Propane operates at comparable pressures and temperatures to R-134a. Most importantly, it involves a 31.4% reduction in energy usage over R-134a.

The disadvantages of propane as a refrigerant result from its flammability. UL-541 regulations would require that units using propane be clearly marked with warnings, have sealed electrical contacts, and provide warning signals if leaks occurred.

In closing, propane (R-290) is a promising substitute for R-134a refrigerant. It is environmentally friendly, compatible, cheaper, more energy efficient, and has the potential to reduce thousands of tons of CO₂ per year.

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References


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