CO_2 Transcritical Cooling with Heat Reclaim

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Abstract
The average global temperature is predicted to rise by between 1.5 and 4.5K in the next 100 years. The principal cause of global warming is the emission of greenhouse gases into the Earth's atmosphere. Supermarkets contribute both directly and indirectly to global warming. Directly, greenhouse gas emissions occur through the leakage of HFC refrigerants used in refrigeration systems for display and storage of food. These refrigerants have very high global warming potential. Supermarkets, however, also indirectly produce CO_2 as they are large consumers of electricity and approximately 50% of this is consumed by refrigeration equipment.

This paper describes a refrigeration system using a natural refrigerant that has been developed to significantly reduce both direct and indirect greenhouse gas emissions. The system uses CO_2 (R-744) as the refrigerant. The CO_2 has very low global warming potential compared with conventional HFC systems which significantly reduces direct emissions. Indirect emissions are also much reduced as the system efficiency is greater than that achieved using conventional HFC refrigerants, due to the heat that can be recovered.

The paper describes a system that has been developed for use initially in convenience stores with a view to applying the same technology to superstores in the future. The second section of the paper outlines the benefits, costs and experience gained from the new system during ongoing trials.

Introduction
Over the last 20 years legislation has prohibited the use of ozone-depleting CFC refrigerants but the use of the HFC refrigerants is still legal and commonplace. In recent years, natural refrigerants have been proposed as an environmentally friendly solution for the refrigeration industry. These refrigerants, including ammonia, hydrocarbons and CO_2, do not contribute to ozone depletion and have low global warming potential.

CO_2 offers a long-term solution suitable for many applications in refrigeration and heating, from domestic applications utilizing heat pumps to provide hot water and space heating in retail applications. The technology is future proof requiring no further retro-fitting to the next refrigerant "solution" promoted commercially.

The transcritical system described has been constructed based on the format used in a typical convenience store. This equates to 50kW of cooling load and a heating load of 38kW. The cooling load comprises medium temperature direct expansion display cases. The heating load comprises two 12kW HFC heat pumps and a 14kW electric door curtain.

R-744 (CO_2) as a Refrigerant

R-744 has been used in refrigeration for many years. Figure 1 shows a timeline from its proposal and discovery, through its decline in the 1930s, to its rediscovery in the 1990s.

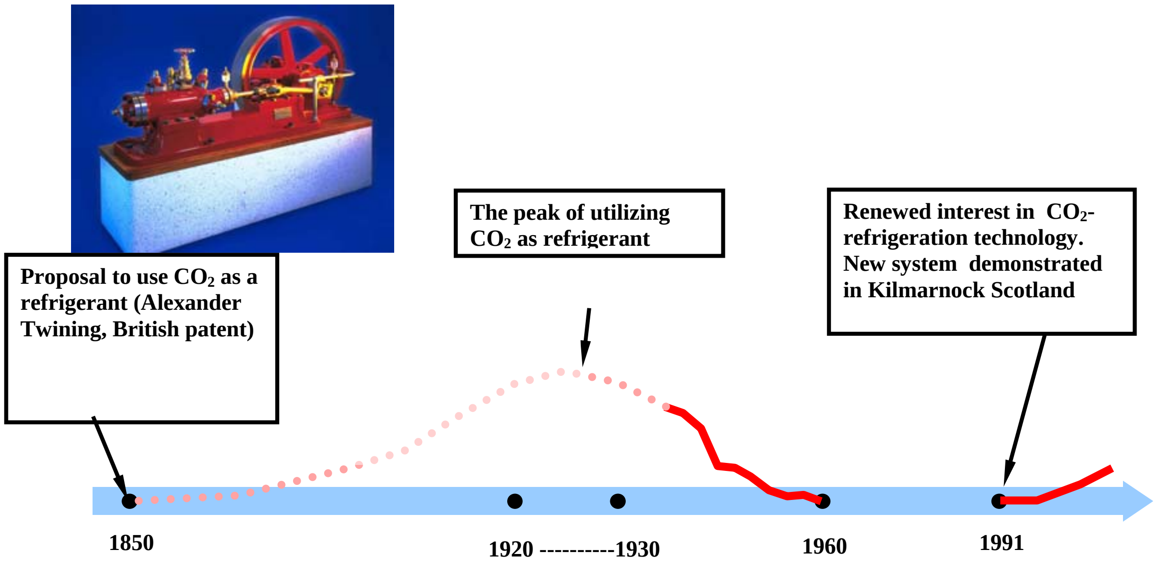

Figure 1: The history of R-744 as a Refrigerant [1] [2]

R744 has ten noteworthy characteristics:

- Non-toxic
- Non-flammable
- Environmentally benign
- Triple Point
- Critical Point
- High pressure
- High Refrigeration Volumetric Capacity
- High heat transfer characteristics
- Inexpensive
- Readily available

Like most natural refrigerants, R-744 is regarded as being environmentally benign. It has an Ozone Depletion Potential (ODP) of zero and very low global warming potential (GWP = 1). The main benefits of R-744 compared to other natural refrigerants are that it is non-toxic and non-flammable, which often limits the application of other refrigerants.

The main characteristics of R-744 as a refrigerant are the critical and triple points. The critical point is at a relatively low temperature at 31^oC at the relatively high pressure of 73Bar and the triple point occurs at -56.6^oC at a pressure of 5.2Bar. CO_2 is the only common refrigerant to have a triple point above atmospheric pressure. Utilising the atmosphere as a heat sink it is not possible to remain below the critical point at the full range of ambient temperatures experienced in the UK. This results in transcritical operation with high pressures and temperatures at compressor discharge. The relationship of temperature and pressure for R-744 can be seen in the simplified P-H diagram (Figure 2).

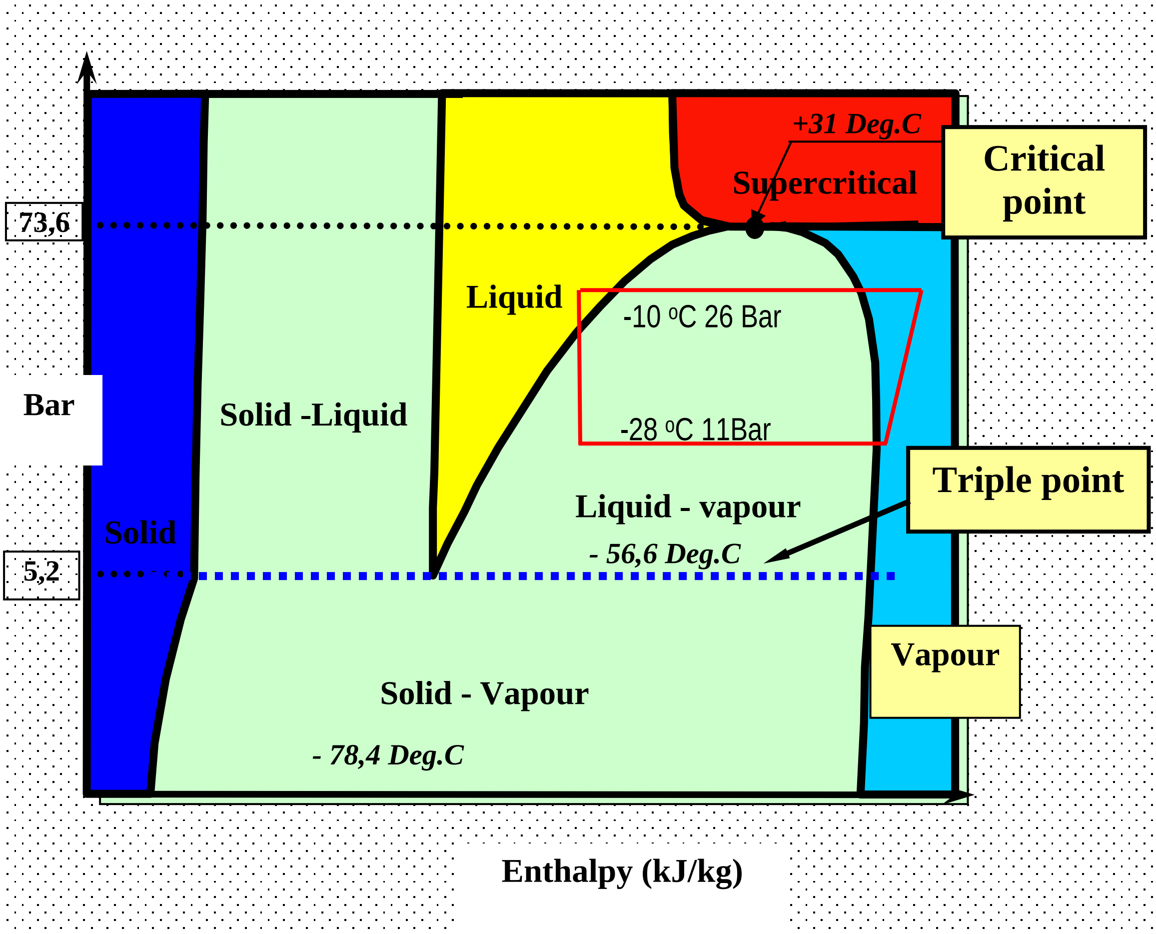

Figure 2. Simplified P-H Diagram [3]

R744 operates at a far higher pressure than standard refrigerants. Figure 3 demonstrates the differences between the operating pressures of standard refrigerants and R744.

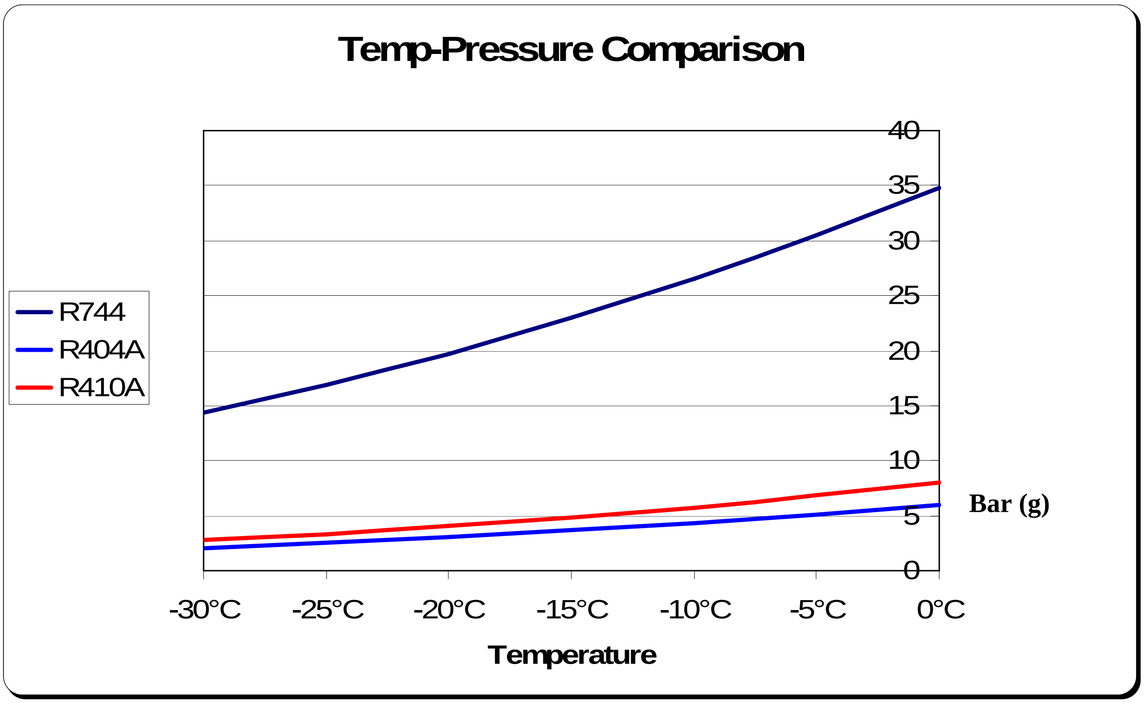

Figure 3. Pressure Temperature Relationship for Various Refrigerants

System Operation

Figure 4 shows a simplified diagram of the system running in transcritical mode. The control strategy is such that the gas cooler control valve can hold the system in permanent transcritical mode or (if heat is not required) allow condensing to take place. Computer modelling using EES software gives the indicated system conditions at a 15^{o}C ambient temperature. Data is currently being collected from the running trial plant. This will be analysed and released when available.

Transcritical CO_2 vapour at 90Bar and 120^{o}C is discharged from the compressor into the heat reclaim unit. This is a shell and tube heat exchanger with a glycol stream passing through a finned coil unit within the building to provide space heating. The finned coil gas cooler further cools the transcritical CO_2 vapour rejecting heat to atmosphere. This vapour is then passed through the pre heater. This is a plate heat exchanger employed to cool the transcritical vapour and heat the superheated vapour entering the compressor. The gas cooler control valve reduces the pressure of the vapour from 90Bar to 35Bar. This re-expansion results in a mixture of saturated liquid and vapour at 35Bar within the intermediate pressure receiver. When heat reclaim is not required the gas cooler control valve is controlled by changes in the gas cooler outlet temperature. At the stated conditions, condensing would be taking place as pressure would be lower than 73.6Bar (see Figure 2). This system, however, can be switched to simulate a gas cooler outlet temperature of 35^{o}C, thus keeping the system transcritical. The intermediate pressure receiver is held at 35Bar to enable copper pipe work to be employed to and from the display cabinets (pressures in excess of this would require stainless steel pipe work). This is achieved by the vapour expansion valve allowing receiver pressure to be relieved to the suction line should it exceed 35Bar. The liquid leaving the receiver is sub-cooled prior to entering the cabinet expansion valves and passing through the cabinet coils. Superheated vapour returning to the compressor is passed through the aforementioned pre heater. Figure 5 shows the system represented on a pressure enthalpy chart.

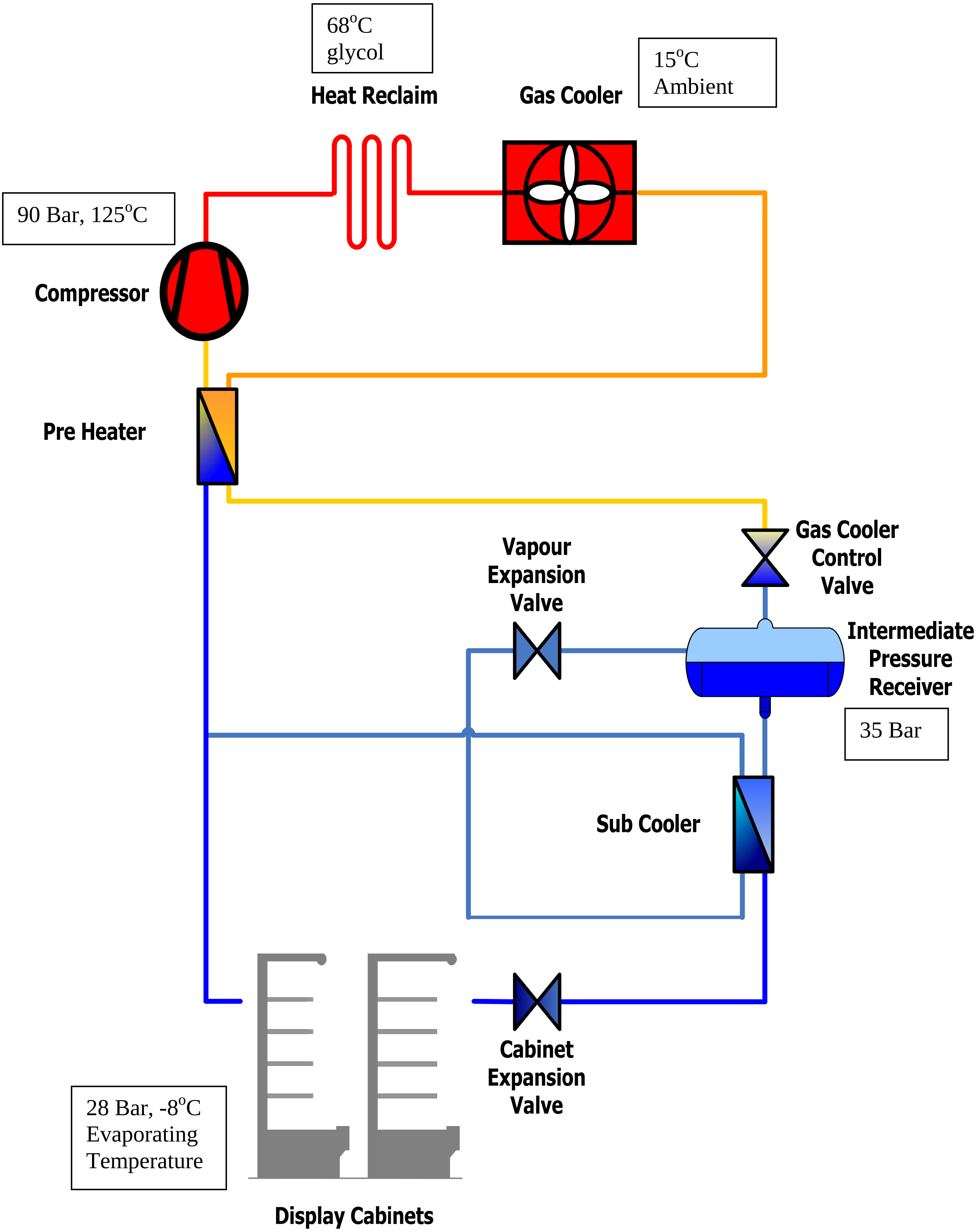

Figure 4. Simplified System Layout (Transcritcal Mode)

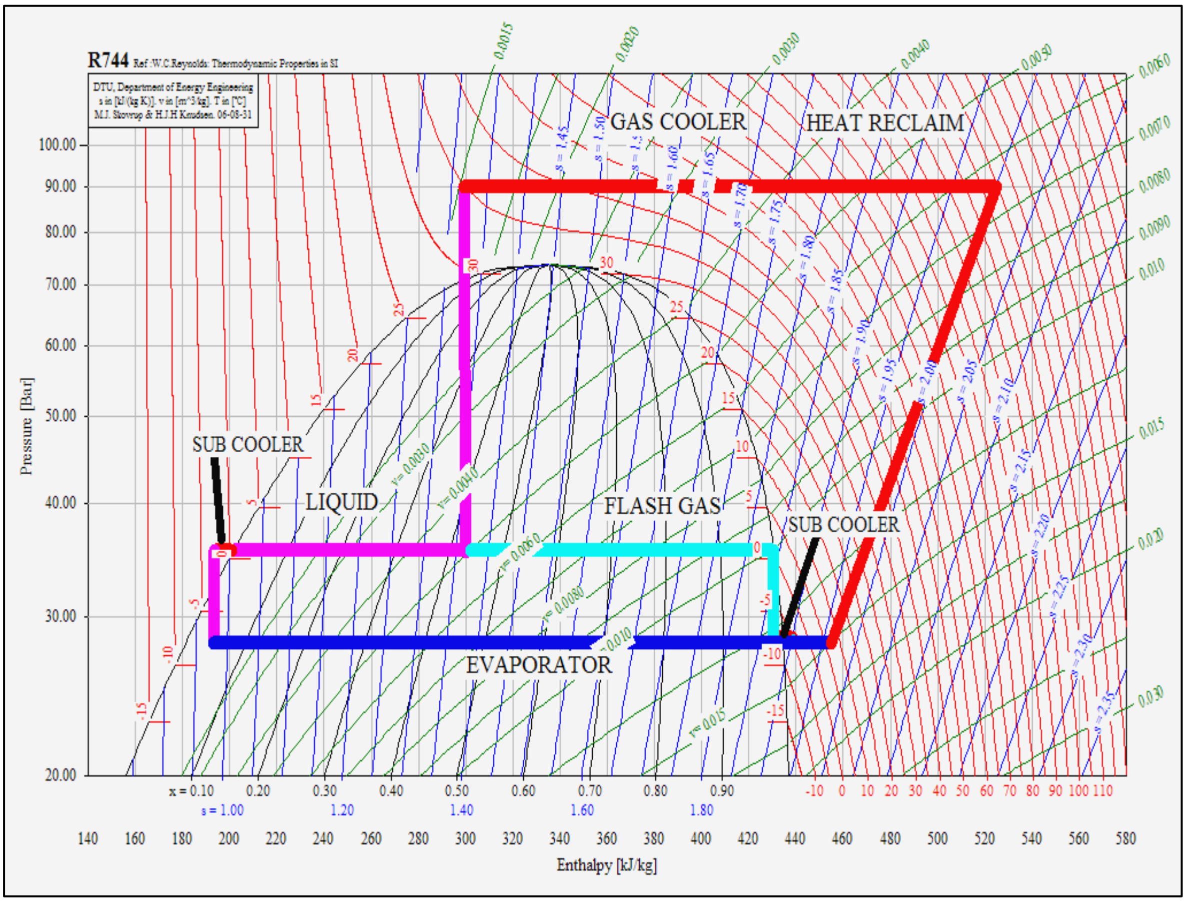

Figure 5. System Cycle Pressure Enthalpy Diagram

Figure 6. Space Engineering Services Trial Plant

Figure 7. Space Engineering Services Trial Plant

Figure 8. Space Engineering Services Trial Convenience Store

System Benefits

During trials, glycol flow temperatures have consistently been recorded between 50^{o}C and 70^{o}C in ambient temperatures of 10^{o}C and below. It is intended to use this recovered heat initially to provide low temperature hot water for the convenience store door curtain, thus removing 14kW of electrical load from the store. As development continues, and reliability is confirmed, further contribution to the store heating load will be considered.

The current R404A HFC refrigeration plant employed for display case cooling in comparable applications could not be considered for store heating. Furthermore, the low GWP of R744 in comparison to R404A offers an environmentally sound solution.

When compared to HFC refrigerants CO_2 displays superior heat transfer properties. This improved performance as a refrigerant will allow a reduction in evaporator coil size when employed at identical evaporating temperatures to an R404A plant. This also means that for identical coil sizes the evaporating temperature can be raised, thus improving system efficiency (see Figure 9).

Other CO_2 systems involve cascade technology and/or pumps increasing their complexity. This system is relatively simple and easy to manufacture.

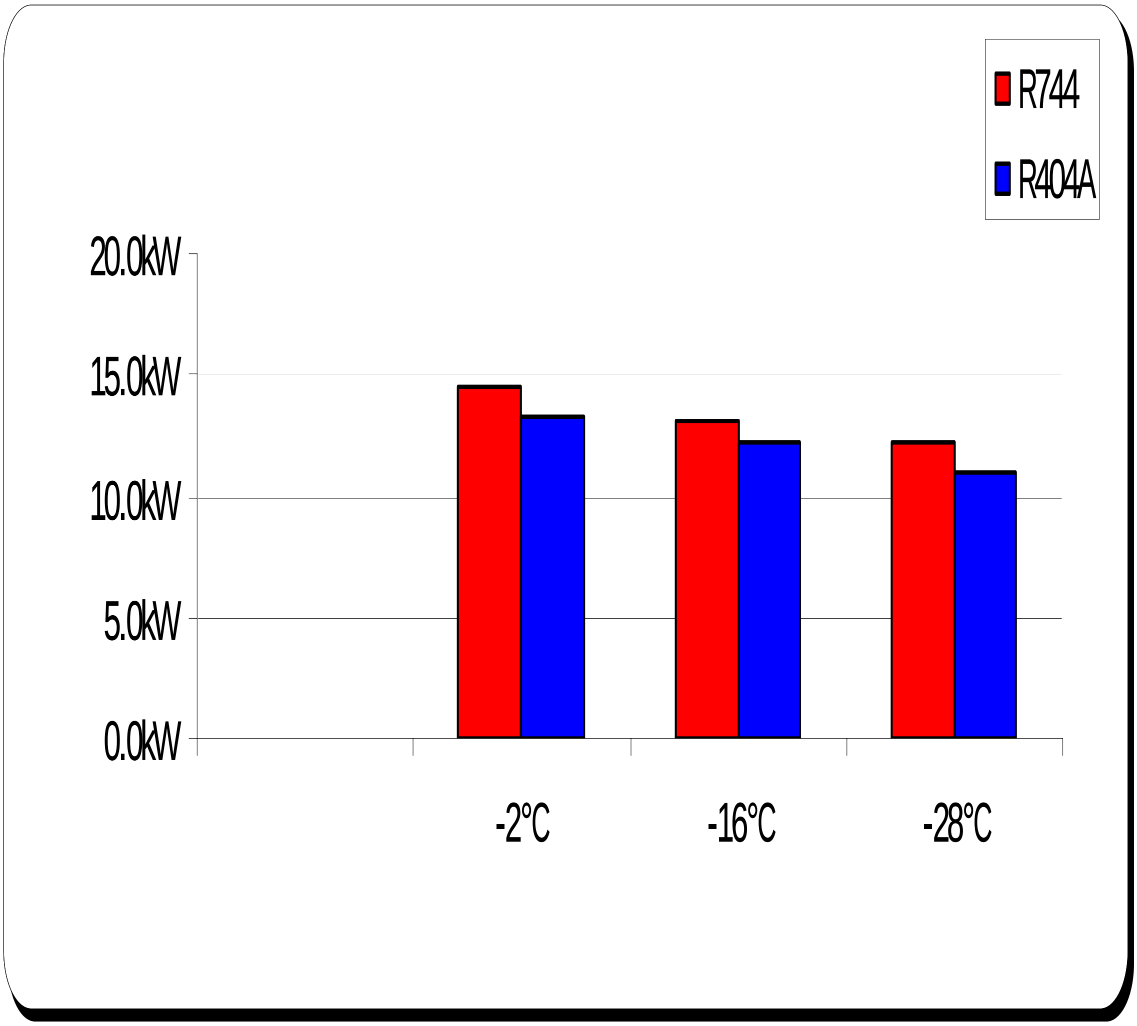

Figure 9. Heat Transfer Comparison (identical coil) [5]

Cost Implications

The capital cost of manufacturing this system currently exceeds the cost of an HFC plant of similar cooling capacity. Due to the high pressures encountered, many components are not available through the usual industry procurement channels. This has meant sourcing components from other industries or developing prototypes. As demand increases and the use of this technology becomes more commonplace, component costs will decrease bringing the unit cost nearer to that of existing HFC plant. Many components obtained as bespoke items here in the United Kingdom are readily available mass manufactured in Denmark where this technology has already been embraced. Refrigerant costs, however, are a fraction of those encountered for HFC refrigerants.

Energy costs are currently being monitored on both an existing convenience store and the trial system. Preliminary calculations for the CO_2 system have indicated a coefficient of performance of 2.9:1 for refrigeration. With the inclusion of the heat reclaim this increased to 3.5:1. Results from the comparison with the existing convenience store will be published when trials are complete.

Learning Points for the Refrigeration Industry

During manufacture, commissioning and trials it was noted that many accepted practices employed while working with HFC refrigerants could not be applied to CO_2. This is due to the higher pressures involved and the fact that the triple point of CO_2 is 5.2Bar. The need has been identified for specialist training for those employed to work with this technology, with some form of industry recognised certification system instituted.

Also encountered was a lack of spares availability. Many components available "off the shelf" for HFC systems had lead times of many weeks for a CO_2 equivalent. Recent indications are that this is improving as manufacturers see the market growing. It is hoped that a comprehensive range of components for this technology will be available in the near future.

Conclusion

The system is relatively simple and trials are producing promising data indicating similar performance figures to HFC systems. This combined with the useable heat recoverable and the environmentally benign refrigerant employed, makes the system a viable candidate for permanently replacing HFC systems. Also, the training, component cost and component availability issues are currently being addressed making the system a commercially viable choice.

References

[1] Danfoss (2002) CO_2 Phase Changes Danfoss [CD Rom]
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[3] Danfoss. CO_2 Refrigerant for industrial Refrigeration, Danfoss 2002 Arhus

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