Performance of a Transcritical Carbon Dioxide Heat Pump for Simultaneous Refrigeration and Water Heating

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ABSTRACT

Many industrial processes require both refrigeration to less than 0°C and water heating to greater than 60°C. Traditional independent refrigeration and boiler systems have relatively poor energy efficiency, whilst conventional heat pumps can provide both cooling and heating but are limited in terms of the temperature lift that can be achieved. A novel heat pump using CO_2 as the refrigerant in a transcritical cycle has been proposed as a new technology that can overcome these disadvantages. The use of CO_2 as a refrigerant has many advantages. It is environmentally benign, safe, and has good thermodynamic properties, especially compared with fluorocarbons. The transcritical cycle involves evaporation of CO_2 at constant temperature and pressure below the critical point to provide refrigeration, while cooling of the CO_2 occurs at temperatures and pressures above the critical point to provide heating of water. The objective of this project was to design and construct a prototype transcritical CO_2 heat pump to simultaneously provide refrigeration and water heating, and to test its performance over a wide range of operating conditions.

The prototype CO_2 heat pump had a nominal cooling capacity of 90 kW at –6°C and nominal water heating capacity of 127 kW from 10°C to 90°C. The prototype was designed to operate with a suction pressure of 30 bar and discharge pressure of 130 bar. The major components were a gas cooler, recuperator, flooded evaporator, low pressure separator/receiver, compressor, expansion valve, connecting piping and a control system. All components were standard high pressure equipment used by the natural gas processing industry. The gas cooler had a reasonably unique design to ensure close to pure counter-current heat exchange between the cooling CO_2 gas and the water being heated, both of which had relatively low flowrates. The compressor used was an open crankcase, reciprocating type with special gas seals on the piston rod to prevent CO_2 leakage. Refrigeration capacity (suction pressure) was controlled by varying the compressor speed. Water heating capacity was controlled by both using the expansion valve to control the CO_2 discharge pressure and varying the water flowrate through the gas cooler.

The main problem encountered during commissioning of the prototype was CO_2 leakage through the compressor piston rod seals. Alternative sealing systems were tried, but the leakage remained an on-going problem that prevented prolonged operation of the prototype, such as would be necessary in industrial applications.

Performance of the prototype was determined by energy balances based on measurements of CO_2 and water flowrate and temperature when it operated at steady-state. The energy balances generally agreed to within 6%. Trials were performed with suction pressures from 29.6 to 35.5 bar, discharge pressures from 80 to 130 bar, with hot water outlet temperatures from 65°C to 90°C, and evaporator water inlet temperatures from 11°C to 21°C.

When heating water to 90°C and providing refrigeration at 1°C (35.5 bar suction pressure), the maximum overall Coefficient of Performance (COP) achieved was 5.4 at a discharge pressure of 114 bar. Below this optimum discharge pressure, the COP

declined due to gas cooler heat transfer limitations (lower compressor discharge temperature led to lower temperature difference in the gas cooler and high CO_2 outlet temperature). Above the optimum, the decline in thermodynamic and compressor efficiency as pressure ratio increased caused the COP to decrease. The maximum heating and cooling capacities were about 13% less than the design values. This was attributed to the lower than expected volumetric efficiency of the compressor. The performance of the heat exchangers were generally close to the design values when allowances for lower than design water flowrates were taken into account.

As expected, when suction pressure was reduced to 29.6 bar (-6°C), there was up to a 10% decrease in optimum COP as well as reduced heating and cooling capacity. When heating water to 65°C rather than 90°C, the optimum COP was about 20% higher. When suction pressure or hot water outlet temperature was decreased, the optimum discharge pressure became slightly lower due to the gas cooler heat transfer being less of a limitation on overall system performance.

Addition of oil to the CO_2 did not reduce the CO_2 leakage sufficiently to allow long-term operation without recharging, and had minimum impact on the performance of the gas cooler, recuperator and compressor. However, oil fouling caused a significant drop in heat transfer performance of the evaporator.

The measured prototype performance agreed well with process simulations of the equipment and with results for similar laboratory scale equipment reported in the literature. Therefore, simulations could be used to optimise component and system design with a reasonable level of confidence. It was shown that the biggest increase in COP could be achieved by improving compressor isentropic efficiency rather than increased heat exchanger size.

Overall, the concept of the transcritical CO_2 heat pump for simultaneous refrigeration and water heating was proven and the required energy efficiency was sufficiently high that the heat pump is likely to be economically competitive with traditional heating and cooling systems. Further work should concentrate on improving compressor design to eliminate CO_2 leakage and to improve both isentropic and volumetric efficiency.

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1 INTRODUCTION

The provision of heating and cooling is a very important function in many industrial processes. In New Zealand an estimated 4700 TJ of energy is used for heating to less than 100°C, and 4500 TJ of energy is used for refrigeration by the food processing industry each year (Kallu and Cleland, 1996). A large proportion of the heating is used to generate hot water for cleaning, sterilisation and other general process heating duties. Often the water needs to be at greater than 80°C due to food safety regulations and other process constraints. Most of the refrigeration is required at temperatures less than 10°C for preservation of food and other perishable products.

Traditionally, heating and refrigeration have been provided separately. This has several advantages. In particular, the amount of heating or refrigeration is easily controlled, and neither is dependent on the other. If only heating or cooling is required at any one time, separate systems are generally more cost efficient.

Cooling is usually provided by vapour compression refrigeration cycles, in which heat is usefully extracted at low temperatures and is rejected to the environment at higher temperatures. Refrigeration cycles at about 0°C typically provide about four times as much cooling as the energy required to drive the compressor.

Heating has been traditionally supplied by boilers. This can be quite cost effective when the price of the fuel for the boiler is low and temperatures greater than 80°C are required. The energy efficiency of boiler systems is typically between 50 and 80%.

An alternative to the use of boilers is passive heat recovery. This is only feasible when an existing process stream is available at sufficiently high temperature. For example, desuperheating of refrigerants after compression in refrigeration systems can provide high temperature heat, but the total heat available at high temperature is usually less than 15% of the total heat rejected from the refrigeration system (White *et al*, 1997). At most sites, there is a large number of options for heat recovery to achieve low temperatures (eg. less than 60°C), but relatively few for higher temperatures.

Another alternative are heat pumps which use the same cycle as refrigeration systems except that waste heat is extracted from the environment and it is the heat of rejection at higher temperatures that is useful. Traditional heat pumps can be energy efficient, typically giving two to six times as much heat as energy consumed (Hewitt *et al*, 1997). However they generally have a high capital cost, and are restricted in the temperatures they can deliver due to loss of efficiency at large temperature lifts and the pressure limitations of commonly available equipment. Conventional heat pumps often use fluorocarbons as the refrigerant, which are currently being phased out due to their ozone depleting and global warming effects.

The use of heat pumps enables the possibility of providing simultaneous heating and cooling. If the heat extracted by the heat pump system is also utilised for refrigeration, much greater overall energy efficiency is obtained. In addition, a single, integrated system requires less space and maintenance than the two separate systems.

Unfortunately, with most conventional heat pump and refrigeration systems, the large temperature split required to provide simultaneous heating and cooling at useful temperatures cannot be achieved without a large loss in efficiency.

Lorentzen (1994) proposed the transcritical carbon dioxide heat pump as a system which is able to efficiently provide high temperature process heat as well as simultaneous cooling. This technology has the potential to be more efficient and cost effective than present systems and also has the advantage of using CO_2 which is naturally occurring and environmentally friendly compared with fluorocarbon refrigerants.

The general objective for this project is to investigate the feasibility of utilising the transcritical CO_2 heat pump cycle for industrial heating and cooling. The project has been organised as part a joint venture between Flotech Ltd, Electricity Corporation of New Zealand Ltd (ECNZ), and Massey University.