CO_2 VAPOUR INJECTED SCROLL COMPRESSORS FOR AIR TO WATER HEAT PUMP APPLICATIONS

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ABSTRACT

The vapour injected scroll compressor can accommodate mid-pocket inter-stage injection and hence enables an economized cycle within one compressor. This enhances CO_2 transcritical cycle performance especially for heat pump applications.
The first part of the paper gives an overview of the transcritical CO_2 cycle applied in air to water heat pumps, its potential and limitations. The discussion is then focused on the intermediate vapour injection with an economizer, its concept and performance.
The second part of the paper evaluates the seasonal efficiency of the transcritical CO_2 cycle with and without vapour injection and a comparison is made with currently available vapour compression cycle technologies using HFCs.

INTRODUCTION

Carbon dioxide is now being rediscovered as a refrigerant in vapour compression systems and is seen as a prospective replacement for HFCs due to its environmental characteristics and its so-called benignity.
This natural refrigerant does not affect the ozone layer and its greenhouse effect is very low compared to HFCs, 1400 times lower than R134a, the lowest Greenhouse Warming Potential refrigerant among all commercially used HFCs. Also, it is neither toxic nor flammable which makes it a preferred choice compared to other natural refrigerants such as Hydrocarbons and Ammonia.

CO_2 has been evaluated in different applications types like refrigerant cascade applications and Domestic Hot Water (DHW) heat pumps where high water temperature can be reached (Winandy and Hundy, 2004).
For Space Water Heating (SWH) in traditional European radiator heating circuits typically with 20K water temperature differentials, the COP of a simple cycle is rather poor compared to other currently available technologies. Different methods of increasing the cycle performance like expander, economizer, internal heat exchanger can be applied (Cavallini, 2004). They have different efficiency effects and cost implications.
One solution evaluated in this paper is the economizer cycle in conjunction with a scroll compressor with vapour injection.

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AIR TO WATER HEAT PUMPS AND CO_2

In order to evaluate the performance of the CO_2 transcritical cycle in a traditional air to water heat pump, the following assumptions have been made:

- Typical compensated water inlet and outlet temperature vs outdoor temperature (Figure 1),
- 5K evaporator temperature difference,
- 10K evaporator superheat,
- 1K Temperature difference between water inlet and gas cooler outlet,
- Air temperature from –15°C to 10°C,
- Constant isentropic efficiency of 0.6 (low pressure ratio range)

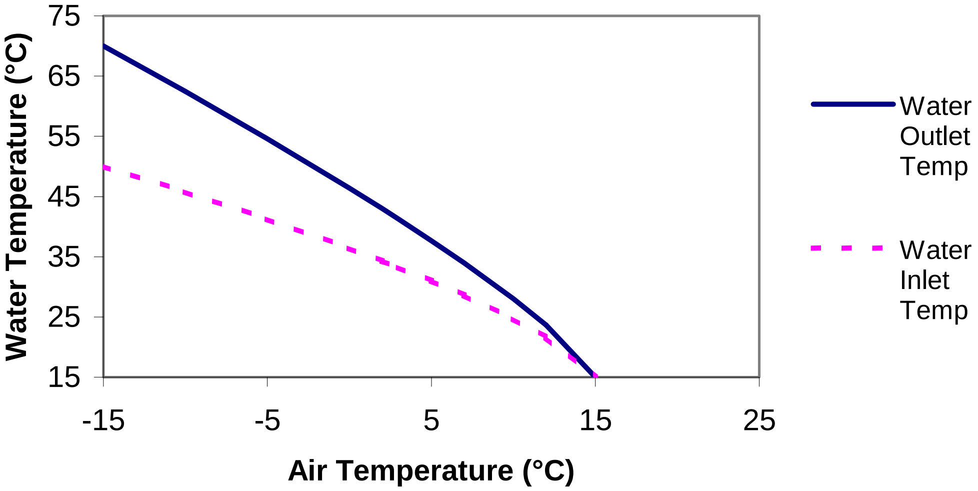

Figure 1. Water inlet and outlet temperature vs outdoor temperature.

The results are presented in Figure 2. As can be seen, there exists an optimum reachable for Air temperature down to –5°C. For these temperatures, it is possible to chose to operate the heat pump either at optimum COP conditions or to boost or to unload the heat pump by increasing or decreasing the gas cooler pressure respectively.

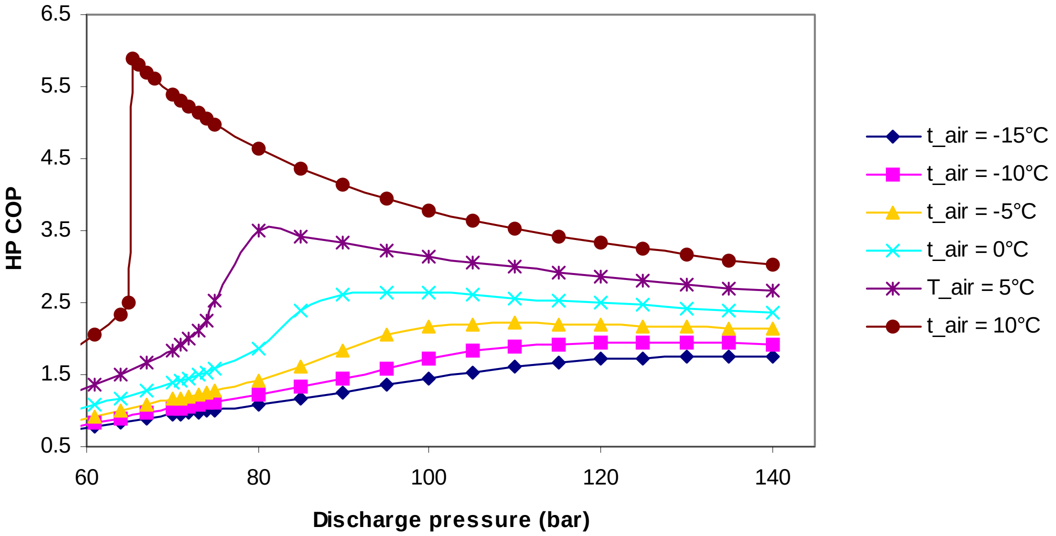

Figure 2. COP vs Gas cooler pressure for a simple CO2 cycle.

For lower outdoor temperatures than –5°C, the maximum COP can only be reached at relatively high pressures. Moreover, the discharge temperature limit is reached before this optimum can be reached due to oil temperature limitations. Indeed, as can be seen in Figure 3, if a maximum discharge temperature of 150°C is fixed as a limit, one can see that the maximum pressure for allowable working conditions is decreasing as the outdoor temperature is decreasing.

This also has the effect of decreasing the heat pump capacity. This trend goes exactly in the contrary direction of the heating demand. On the other hand, from an energy efficiency point of view, since the COP curves are rather flat, the COP at maximum pressure is not far from the optimum one.

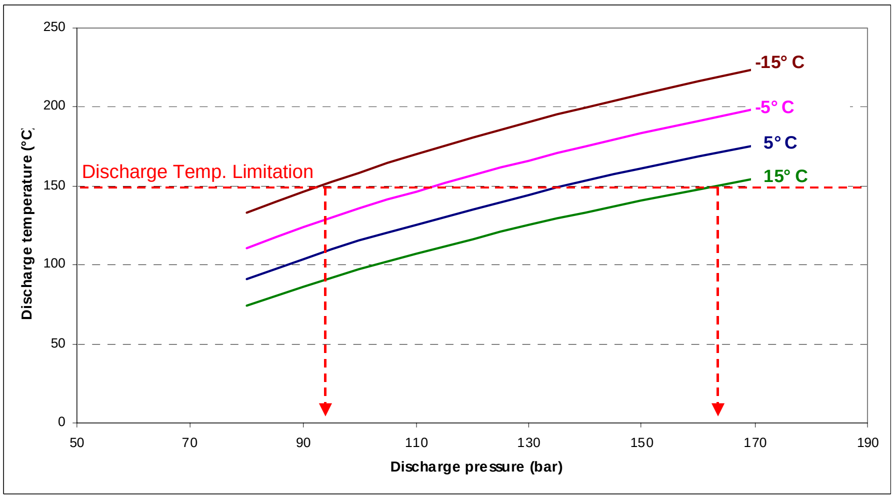

Figure 3. Discharge temperature vs Gas cooler pressure for a simple CO2 cycle.

The economizer cycle has the potential to increase the COP and to decrease the discharge temperature.

CO_2 CYCLE WITH VAPOUR INJECTION

The vapour-injected scroll compressor cycle is similar to a two-stage cycle with interstage cooling, but accomplished with a single compressor as shown in Figure 4. For the vapour compression cycle the high stage is accomplished by extracting a portion of the condensed liquid and expanding it through an expansion valve into a counterflow brazed-plate heat exchanger acting as a subcooler. The superheated vapour is then injected into an intermediate vapour injection port in the scroll compressor. The additional subcooling increases the evaporator capacity by reducing its inlet enthalpy and the additional mass flow increases the condenser capacity (Beeton and Pham, 2003).

The technique can be applied to the CO_2 transcritical cycle and in this case a portion of the high pressure gas is passed through an expansion device and forms two phases at an intermediate pressure. The remaining high pressure gas which has passed through the gas cooler is further cooled by evaporation of CO_2 at the intermediate pressure as shown in Figure 5.

Capacity gain

Because the vapour injection occurs after closure of the suction port, the compressor inlet volume flow rate and hence mass flow rate of suction gas is almost unchanged by the addition of the injected refrigerant. The added capacity is achieved by enhanced mass flow across the gas cooler. The compressor displacement required for a given load can therefore be reduced.

For capacity modulation at lower capacities may be achieved by turning off the vapour injection circuit.

COP gain:

The vapour-injected scroll compressor cycle efficiency is higher than the conventional single-stage delivering the same capacity because the added capacity is achieved with less power: the incremental vapour created in the intermediate evaporation process is compressed only from the higher interstage pressure rather than from the lower suction pressure.

Compressor Cooling Effect

The injected vapour has a cooling effect on the compression process and this ensures that the scroll can cover a broader range of operating conditions necessary for air to water heat pumps without the need for additional liquid injection or oil cooling.

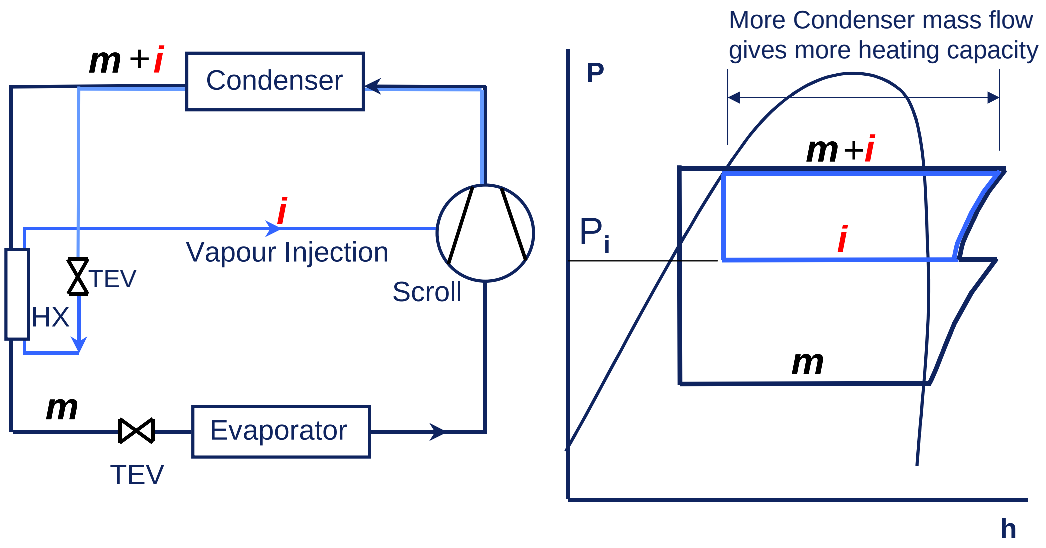

Figure 4: Vapour-injected scroll compressor with enhanced vapour compression cycle

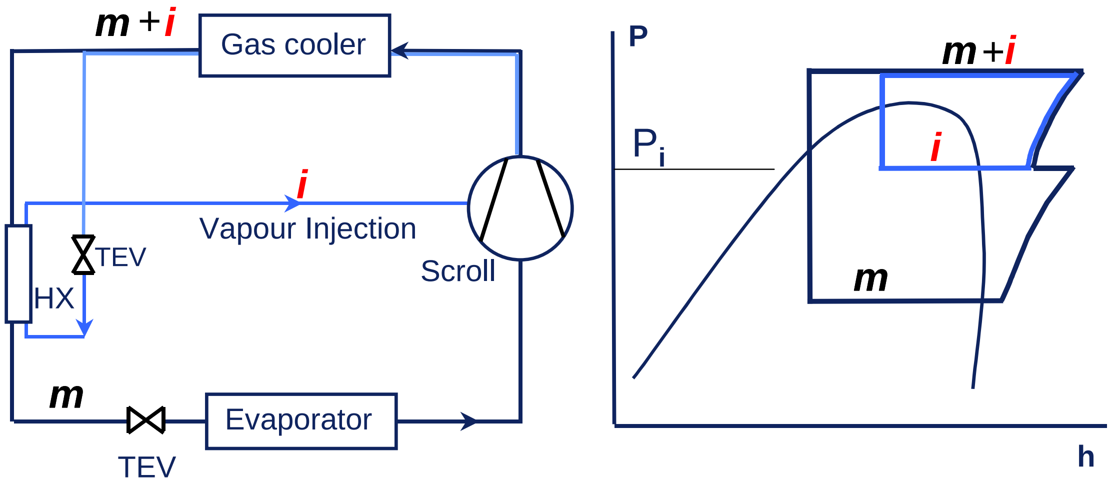

Figure 5: Vapour-injected scroll compressor with enhanced CO2 transcritical cycle

Table 1 shows the calculated results obtained with the assumptions established in the first part of this paper and:

- Vapour injection considered as a 2-stage cycle
- Intermediate injection pressure of the square root of the product of discharge and suction pressure,
- 5K Economizer approach temperature: temperature difference between subcooled CO_2 (point 8 in Figure 6) and vapour inlet (point 6 in Figure 6)
- 5K Economizer superheat (point 7 in Figure 6)

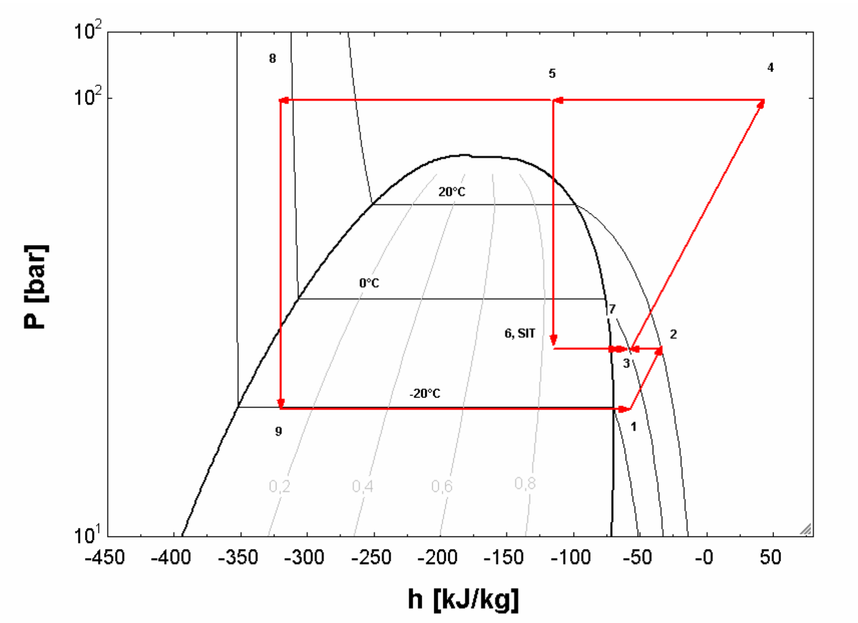

Figure 6: Transcritical Cycle with Vapour-injected scroll compressor at typical conditions

Note that the intermediate injection pressure can be adjusted to optimise the COP or the heating capacity or simply to broaden the operating range by keeping discharge temperature under certain limits. The results show COP increase up to 50% at the lowest outdoor conditions. The effect decreases for higher temperatures since the vapour injection benefit is linked to the pressure ratio.

Air Temperature (°C)	Evaporating Temperature (°C)	Exhaust Gas Cooler Temperature (°C)	COP HP BASIC	COP HP EVI	COP Increase With EVI
-15	-20	51	**1.26**	1.91	52%
-10	-15	46.8	**1.73**	2.11	22%
-5	-10	42.3	**2.21**	2.41	9%
0	-5	37.4	**2.65**	2.89	9%
5	0	32	**3.51**	3.81	9%
10	5	25.7	**5.88**	6.15	4%

Table 1. COP Comparison with and without vapour injection

SEASONAL EFFICIENCY COMPARISONS

Based on the same assumptions as described in the first part of this paper, Table 2 shows the results of Seasonal COP calculations for two different cities, Lyon and Stockholm and for four different technologies: CO_2 transcritical cycle, CO_2 transcritical cycle with vapour injection, R407C basic cycle and R407C with vapour injection based on available data (Copeland, 2005).

An improvement of up to 12% in SCOP can be expected with Vapour injection when comparing a vapour injection CO_2 cycle straightforward CO_2 transcritical cycle.

When comparing refrigerants, it is found that the seasonal efficiency of a basic R407C cycle is up to 28% better than a basic CO_2 cycle. The vapour injection cycle for CO_2 only decreases this difference to about 19%. On the other hand, if we compare the two refrigerants with the same technology, an improved CO_2 transcritical cycle with vapour injection gives a seasonal efficiency up to 27% lower than the corresponding R407C cycle.

	CO2			R407C			Comparison R407C/CO2		
	SCOP non VI	SCOP VI	CO2 VI Vs non VI	SCOP non VI	SCOP VI	R407C VI Vs non VI	R407c Vs CO2 non VI	R407c Basic Vs CO2 VI	R407c Vs CO2 VI
Lyon Climate	3.28	3.53	7.5%	4.22	4.40	4.4%	28.3%	19.3%	24.6%
Stokholm Climate	2.58	2.90	12.3%	3.20	3.68	15.0%	23.9%	10.3%	26.8%

Table 2: Comparison of SCOP with CO_2 and with R407c
with basic and Vapour Injection (VI) cycles

CONCLUSIONS

The introduction of vapour injection with CO_2 transcritical cycle results in significant efficiency improvement when compared to the simple transcritical cycle, but for water heating systems which can operate with a small differential temperature, the benefits do not result in efficiencies obtainable with the HFC vapour compression cycle. If there will be a place for vapour injected CO_2 systems then this is likely to be where there is a significant service demand for high temperature water which can make effective use of the high temperature gas in the first stages of cooling in the gas cooler, in addition to the space heating requirement.

The potential to achieve high flow temperatures is an important consideration because although there are few hours at low ambient conditions, it is under these conditions that the vapour compression cycle is most limited, and may not be able to deliver the heat requirement. The limiting condensing temperature for these systems is normally 65°C and this can become reduced to 60°C at low evaporating temperatures.

The benefit is much greater at lower evaporating temperatures and so under very cold climatic conditions, and particularly where the heat dissipation surface is limited, the Vapour Injection transcritical cycle could enable the application of cost effective space heating systems.

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