Reversible CO_2 Heat Pump with Ejectors for Efficient Heating and Air-Conditioning

Jonas Schönenberger, Frigo-Consulting AG, Switzerland

A renowned shopping centre in the area of Lucerne, Switzerland, was modernised in 2019/2020. In this context, the existing fossil heating and air conditioning system was replaced by two reversible air-to-water CO_2 heat pumps with ejectors. The two heat pumps cover a heating capacity of 1.1 MW and an air conditioning capacity of 1.3 MW. Higher investment and life cycle costs were accepted in order to develop sustainable and forward-looking technologies with natural refrigerants. The project was supported by the Swiss Federal Office of Energy. Since the commissioning of the heat pumps, their operation has been investigated, and valuable experience has been gained.

CO_2 first appeared as a refrigerant in the middle of the 19th century. In the first half of the 20th century, CO_2 was replaced by the so-called safety refrigerants. As the ozone hypothesis first emerged in 1974, politicians reacted and adopted the Montreal Protocol in 1987. Since then, regulations and bans on synthetic refrigerants have been steadily increased. In the meantime, we arrived at the fourth generation of synthetic refrigerants, the so-called HFOs. These are currently being propagated by the chemical and refrigerant industry as a supposed solution, although their decomposition products can accumulate in surface water, are difficult to degrade and can thus also end up and cumulate in drinking water. It is to be expected that the HFO refrigerants, like their three previous generations, do not represent a long-term solution and the only future-proof refrigerants are the natural ones. These are mainly carbon dioxide (CO_2), ammonia (NH_3) and the group of hydrocarbons (propane, etc.).

Reversible heat pump

The commercial refrigeration system of the supermarket within the shopping mall is based on a CO_2 booster system with ejectors. The waste heat of the CO_2 booster system is used in priority for domestic hot water and facility heating. Any additional heating or air-conditioning demand is covered by the two reversible air-to-water CO_2 heat pumps. The reversible heat pumps are also equipped with ejectors to eventually achieve the highest possible efficiency. Table 1 shows the most important key figures of the reversible air-to-water heat pumps.

Table 1. Key figures of the air-to-water CO_2 heat pumps.

	Heating mode	Air-conditioning mode
Nominal capacity per heat pump (2x)	550 kW_{th}	630 kW_{th}
Ambient temperature	-8°C	+36°C
Temperature level	+30°C/+50°C	+12°C/+7°C
Gas cooler outlet temperature	+32°C	+38°C
High pressure	80 bar	95 bar
Evaporation pressure evaporator	-15°C	+5°C
Evaporating pressure compressor	-10°C	+10°C
Evaporator (2x)	3 x 125 kW_{th} (air)	2 x 315 kW_{th} (water)
Gas cooler (2x)	2 x 275 kW_{th} (water)	3 x 285 kW_{th} (air)
Compressor (2x)	6 pieces, 1 frequency converter (30 to 60 Hz)	
Ejectors (2x)	5 pieces, variable motive flow	
Piping lengths (between)	rack - gas cooler, one way: 75 m rack - heat/cold storage, one way: 150 m	
Heat/cold storage (each)	10 m^3 water	

Figure 1 shows the selected principle of the heat pumps, heating mode on the left, air-conditioning mode on the right. The pre-compression of the ejectors is visible in Figure 1. In heating mode, the CO_2 is pre-compressed from 23 bar to 27 bar. This corresponds to an evaporation temperature at the compressor of -10°C, which is above the air outlet temperature of -12°C. In air-conditioning mode, the CO_2 is pre-compressed from 40 bar to 45 bar. This corresponds to an evaporation temperature at the compressor of +10°C, which is above the cold-water outlet temperature of +7°C. In the so-called "dual" operation mode, heating and air-conditioning can be provided simultaneously.

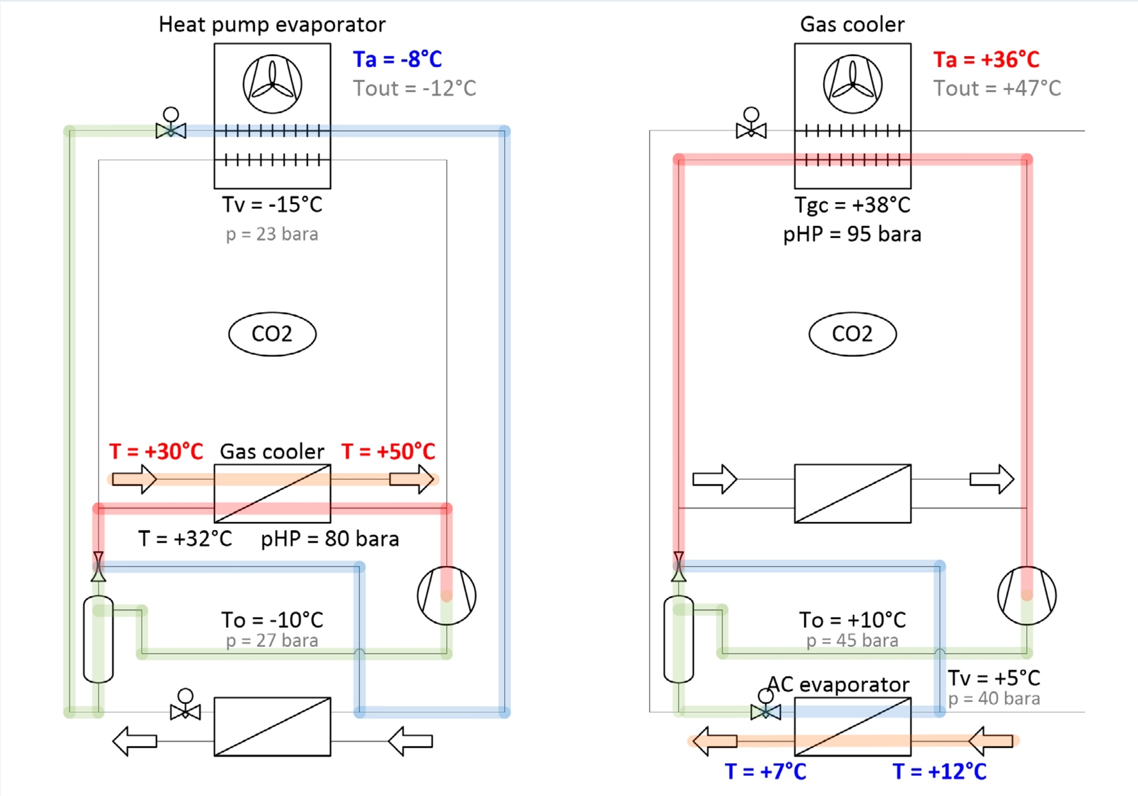

Figure 1. Schematic diagram of reversible air-to-water CO_2 heat pumps, left: heating mode, right: air-conditioning mode.

The heat pumps maintain the temperature level in the thermal storage for heating and air-conditioning. The frequency is controlled, and compressors are switched on and off to maintain the setpoint temperatures. The high pressure is controlled by the ejectors according to the optimum high-pressure setpoint, based on the gas cooler outlet temperature. The expansion valve controls the superheating of the evaporators. The evaporating pressure (evaporator), the medium pressure (evaporating pressure at compressor) and the resulting pressure lift of the ejectors adjust themselves, i.e., are not controlled. The water temperatures for heating and air conditioning are controlled on the waterside to the setpoint by the control valves. Figure 2 shows the project scope of the installed systems on-site.

Operation Modes

At each point in time, each heat pump is assigned an independent, defined operating mode according to Figure 3. If at least one (1) measurement value per time increment is missing, the point in time is assigned to the operating mode "Gap". When a heat pump is not in operation, that point in time is assigned to the operation mode "Standby. For the active operating modes, a distinction is made between "Chiller", "Dual", "Heat pump", and "deFrost". The operating modes "Heat pump" and "Chiller" are of particular interest for the evaluation and especially for the comparability with other systems. The "Dual" and "deFrost" operating modes depend strongly on further parameters so that a comparison with other systems is difficult.

Operation Investigation

The following operational investigation is based on measurement data from the beginning of October 2020 to the end of September 2021. During the mentioned period, no fundamental changes on a component-level or control strategy of the system have been done. Accor-

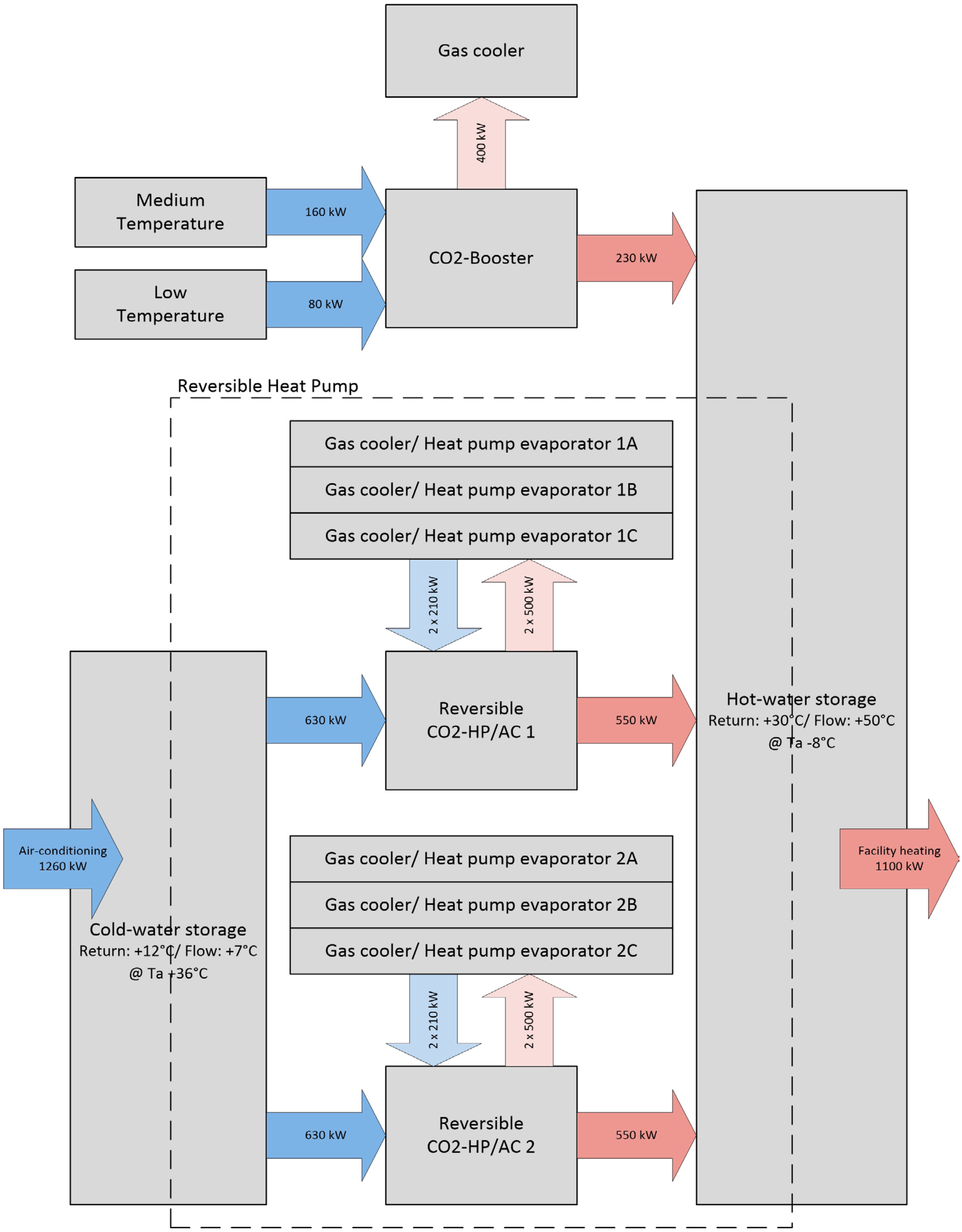

Figure 2. Overview of the CO_2 booster system and reversible CO_2 heat pumps installed on site.

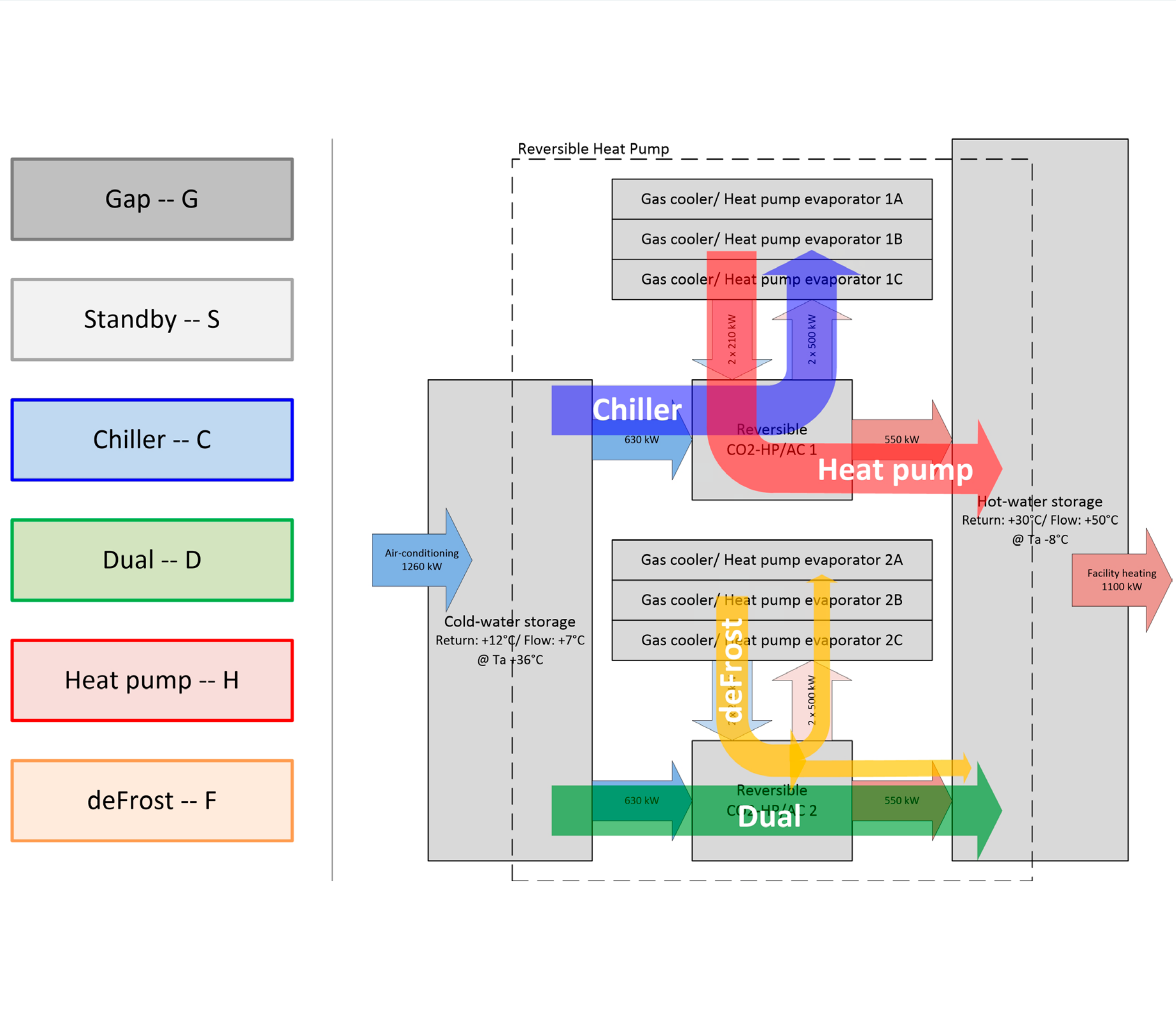

Figure 3. Defined operation modes of the reversible heat pumps.

ding to the Swiss federal office of meteorology and climatology, the winter of 2020/21 and the summer of 2021 were characterised by above-average rainfall amounts according to their climate bulletins. The mean temperature was above the long-term average. There was no extreme, prolonged cold in winter 2020/2021 and no extreme, prolonged heat in summer 2021. Due to the high rainfall amounts, the humidity in the environment was, in part, significantly higher.

Heating

Figure 4 shows the average measured and predicted coefficient of performance (COP) during heating mode and the total provided heating energy of both heat pumps. The red, thick points correspond to the measured averaged values; the thin red line represents the predicted COP (model: operation). Weighted by the provided heating energy, the measured COP is -1.0% below the predicted COP over the entire temperature range. The annual performance factor of the heating mode is 3.33, without considering the dual-mode (simultaneous heating and air-conditioning).

The measured COP is lower than the predicted COP in the upper-temperature range. According to current knowledge, the flattening and gradually decreasing COP in heating operation in the upper-temperature range can be attributed to partial load operation. This is very significant in heating mode, especially since several effects accumulate. Over the year (annual performance factor), however, this effect is limited, especially since the energy demand in this temperature range also decreases significantly.

In the lower temperature range, the measured COP is higher than the predicted COP. Based on current knowledge, this can be attributed to the lower return flow temperatures of the facility heating during operation. This effect can be modelled relatively easily and can be considered in future calculations. Furthermore, this confirms the necessary rethinking for an efficient application of CO_2 heat pumps compared to conventional heat pumps. In contrast to conventional heat pumps, the efficiency of CO_2 heat pumps is not primarily determined by the forward flow temperature but by the return flow temperature and its temperature spread between flow and return temperature.

Air-conditioning

Figure 5 shows the average measured and predicted coefficient (COP) of performance in operation and the total provided air-conditioning energy of both heat pumps. The blue, thick points correspond to the measured averaged values; the blue, thin line represents the predicted COP (model: operation). Weighted according to the air-conditioning energy provided, the measured COP is -3.1% below the predicted COP over the entire temperature range. The annual performance factor in air-conditioning mode is 5.32 without considering the dual operation mode.

According to current knowledge, the lower COP in air-conditioning operation at lower ambient temperatures is mainly due to partial load operation and increased cycling of the heat pumps. Partial load operation becomes increasingly important in air-

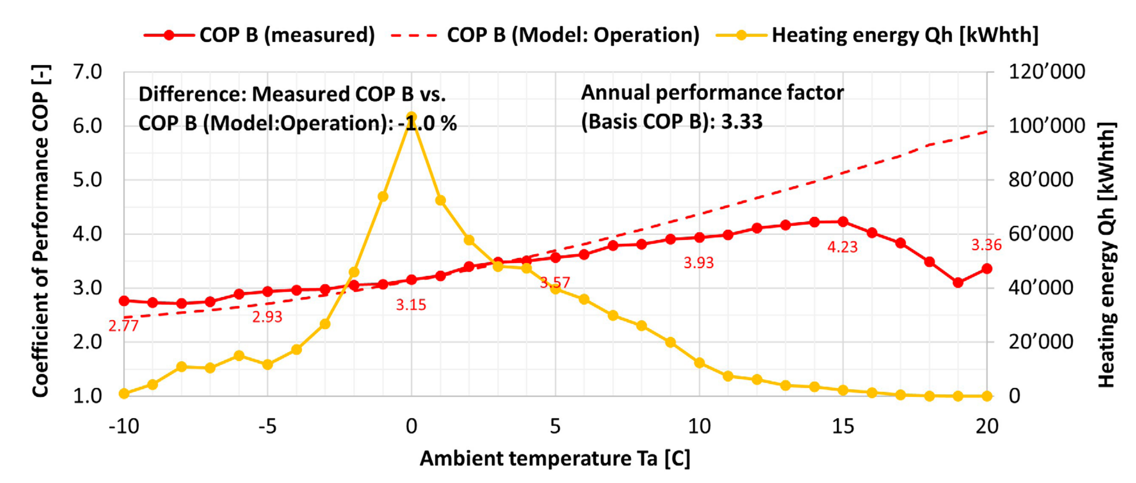

Figure 4. Average COP (heating mode) and total heating energy as a function of the ambient temperature of both heat pumps.

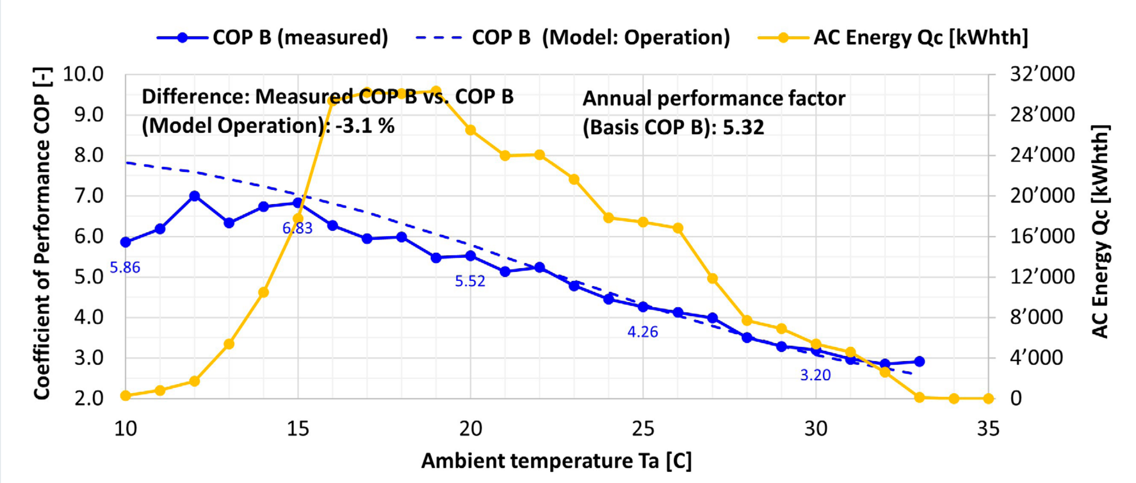

Figure 5. Average COP and total air-conditioning energy depending on the ambient temperature of both heat pumps.

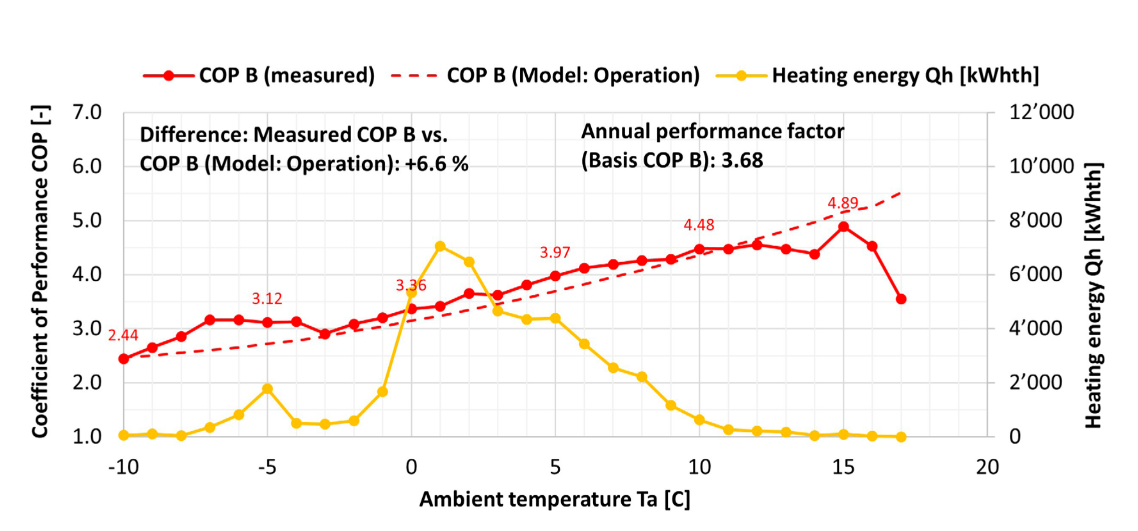

Figure 6. Average COP (heat pump) and total heating energy as a function of the ambient temperature of the heat pump installed at a follow-up Jobsite.

conditioning operation towards lower ambient temperatures, as it does in heating operation towards higher ambient temperatures. In addition, as the ambient temperature decreases, the high pressure (motive pressure) of the ejectors decreases and the suction effect of the ejectors decreases accordingly, which in turn makes stable process control noticeably more difficult. Over the year (annual performance factor), the measured COP values are 3.1% below the predicted values. In contrast to the heating mode, these points are more significant over the year, as the measured values are lower than the forecast in a relevant temperature range.

Conclusions

In summary, the reversible air-to-water CO_2 heat pumps with ejectors have been operating successfully since autumn 2019. Valuable knowledge has been gained about their operating behaviour and the individual operating modes. In the meantime, a follow-up Jobsite based on the same CO_2 technology has already been successfully commissioned. The measured increase in efficiency at the mentioned follow-up Jobsite underline that relevant conclusion were drawn from the first Jobsite and that these were successfully incorporated.

Figure 6 shows the coefficient of performance (COP) of a follow-up Jobsite. The COP in heating mode could be increased from -1.0% to +6.6% compared to the model. The annual performance factor during heating mode of the follow-up Jobsite is 3.68 compared to the annual performance factor of 3.33 in the first Jobsite. This compairision is without taking the dual operation into account.

The outlook to the follow-up Jobsite confirms that adjustments in the system design and operation result in an increase in the COP of around +8 % compared to the model. It can be assumed that a further increase in efficiency can be achieved in further follow-up Jobsites. In addition to the energy optimisations, the system was simplified, and investment and operating costs were reduced. Considering the ecological concerns with synthetic refrigerants, as well as the fact that CO_2 is neither toxic nor flammable and, finally, the progress achieved in terms of efficiency, makes the authors confident that reversible air-to-water CO_2 heat pumps with ejectors will play a relevant role in future for heating and air-conditioning of modernised buildings.

JONAS SCHÖNENBERGER
Frigo-Consulting AG
Switzerland
j.schoenenberger@frigoconsulting.ch
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