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CO_2 refrigeration and heat pump systems

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Delivered		
Author(s) Name	Organisation	E-mail address
Hagar Elarga	NTNU	hagar.elarga@ntnu.no
Prem Kumar Sherman	NTNU	
Armin Hafner	NTNU	armin.hafner@ntnu.no

Contents

List of Figures

List of Tables

1. PREFACE

A dedicated section on the project website will hold the educational material – including manuals, guidelines, books, case study files for computational software and other material – and allow for a basic filtering of information for easy access of website users (available also in South European languages). The material, developed by all project partners throughout the project will be made available as free downloads and for direct integration into supranational, national, and regional conferences and workshops. Educational and knowledge-building promotional material presented will be a direct result from the MultiPACK project activities but might also list other case studies and material in line with the project's core ambition to familiarise the HVAC&R market stakeholders, as well as legislators and the wider public, with available efficient integrated heating and cooling solutions. Specific material will also be developed for addressing individual target groups, taking into considerations their peculiarities, as for example, in the case of big supermarket chains, small family-owned shops, hotel chains, public institutions.

The present deliverable includes all the contents of the third educational e-book from MultiPACK. The latest version of the e-books, with the correct design and formatting is always available at: Downloads section of the project's website.

2. INTRODUCTION

Classification of CO_2 only refrigeration systems

The path to adopt an environmentally efficient and integrated “CO_2 only” systems which accommodate not only the commercial refrigeration requirements but also the heating, domestic hot water supply and the cooling demands of diverse buildings’ could be categorized by

- Without the multi ejectors component
- With the multi ejectors component

Multi ejector component

Traditional ejector refrigeration system are thermal driven cycles and have been used for cooling applications over many years. The ejector has three zones. 1. Suction zone, downstream of the motive nozzle where the reduced pressure, due to high velocities enables a suction flow of vapour into the ejector from the evaporator. 2. Mixing zone, where the two flows from motive side and from evaporator side is mixed. 3. Diffusor zone where the high velocity in the mixing zone is further reduced and builds up pressure when passing though the diffusor zone.

The high-pressure fluid is expanded trough the motive nozzle, i.e. its internal energy converts to kinetic energy. The high-speed motive stream entrains a low-pressure suction stream in the suction entrance. In this way, it is possible to lift the fluid of the low-pressure side to a higher-pressure level by the expansion work via the ejector.

In refrigeration systems there are many different configurations where ejectors can be utilized. In this e-book only brief descriptions of simplified systems are described where the expansion valve is replaced with an ejector. The motive fluid downstream of the heat rejection devices is expanded in the motive nozzle. This will entrain a low-pressure suction stream from the evaporator. Both streams enter the mixing section where they exchange momentum, kinetic and internal energies and become one stream with almost uniform pressure and velocity. The stream converts its kinetic energy into internal energy in the diffuser to reach a pressure higher than the suction vapour inlet pressure

In this educational report several different CO_2 systems listed in table- 1 “before and after the multi ejector concept” are explained through three main subsections of:

- System description
- PH diagrams
- Control approach

Table 1 List of systems

Baseline booster unit, without ejectors

System-1 "CO_2 only" Refrigeration and heat recovery system"

The simple two stage transcritical CO_2 system shown below is considered as a first-generation CO_2 booster refrigeration system for commercial i.e. supermarkets use.

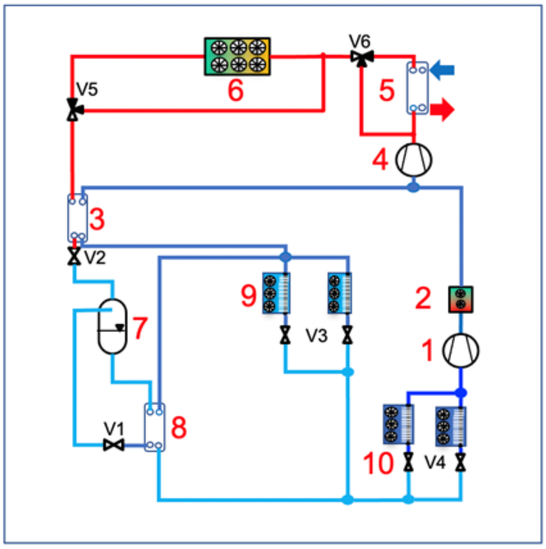
Hot gas discharged from the medium temperature compressor(s)[4] flows on demand into the heat recovery[5] device, otherwise straight towards either; the gas cooler[6] through the bypass valve [V6] or the IHX[3] through bypass valve[V5] depending on the building demand and system valves control characteristics.

The refrigerant exit temperature from the gas cooler is a function of its size and the ambient temperature. The control system decides the set-point for the high side pressure level, subcritical or transcritical, depending on the exit temperature or the heating demand.

The high-pressure gas is subcooled through the internal heat exchanger[3] before entering the high pressure control valve[V2]. Downstream of the high-pressure control valve, the liquid/gas is separated in the separator[7]. The gas expands through [V1] and is superheated through IHX[8]. Whilst, the liquid leaves the separator[7] at the bottom towards the IHX[8] to be subcooled and later supplied to the MT and LT evaporators. The electronic valves [V3] and [V4] are the feeding valves for the evaporators to maintain the temperature setpoint values at the different cooling spots. Downstream of the LT evaporators[10], the superheated vapour is compressed by the LT compressor(s)[1].

The flash gas bypass valve FGBV [V1] maintains the separator's pressure level by throttling a dedicated amount of vapor towards the MT suction port, upstream of the IHX [3]. The desuperheater[2], downstream of the LT compressors, rejects some heat to reduce the refrigerant temperature before mixing with the leaving fluid from the MT evaporators and the FGBV which passed through IHX[3] prior compression of the MT compressors [4].

Table 2 System 1: Baseline CO_2 Booster system

	Components	Scheme
1	Low temperature compressor(s)	
2	Desuperheater (air cooled)	
3	Internal heat exchanger, IHX	
4	Medium temperature compressor(s)	
5	Heat recovery device	
6	Gas cooler (air cooled)	
7	Liquid separator	
8	Internal heat exchanger	
9	Medium temperature evaporator(s)	
10	Low temperature evaporator(s)	
--	---	
V1	Flash gas bypass valve FGBV	
V2	High pressure control valve	
V3	MT evaporator(s) feed valves	
V4	LT evaporator(s) feed valves	
V5	Bypass, gas cooler valve	
V6	Bypass, heat recovery device	**Generalized system**

note: the control of the LT feeding valve V4 secures sufficient superheating up to the suction flow towards the LT compressor(s).

❖ **PH diagram and thermodynamics analysis Figure-1**

The refrigerant leaving the gas cooler/condenser (thermodynamic process 6, identifying the high pressure HP) and cooled through IHX[3] (thermodynamic process 3) is expanded through the high pressure control valve (thermodynamic state 7). The mixed vapor/ liquid fluid is separated, while the liquid is further cooled by IHX8 (thermodynamic process 8), thereafter expanded into the medium and low temperature evaporators respectively. The saturated vapor leaving the MT evaporator(s) (thermodynamic process 9), is mixed with the expanded and superheated flash gas through [V1] and IHX[8] (thermodynamic process 8) respectively. The mixture is further superheated through IHX[3](thermodynamic process 3) and thereafter mixed with the compressed (thermodynamics process 1) and de-superheated (thermodynamics process 2) fluid leaving the LT evaporator (thermodynamics process 10). This mixture is subsequently compressed to the HP (thermodynamics process 4). The heat recovery process for different purposes is executed through (thermodynamics process 5) before entering again into the gas cooler to complete the cycle.

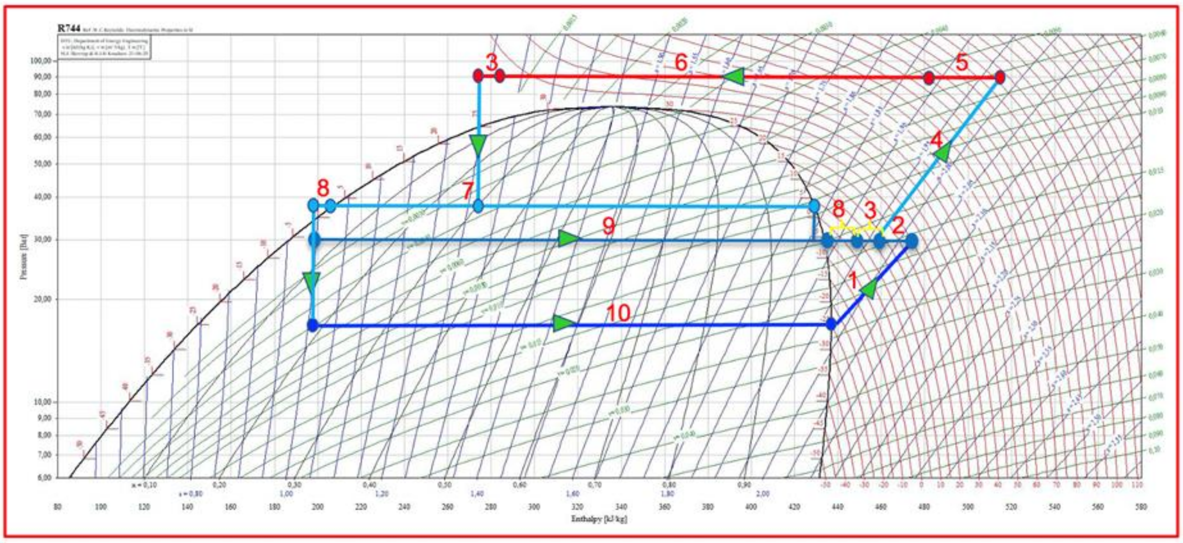


Figure 1 System-1 PH-diagram

❖ **Control approach**

The main system controller typically has several PI type sub-control loops which are controlling system components i.e., valves, MT compressor(s) and LT compressor(s).

-The HP setpoint value is continuously reset (adjusted) in accordance to the control strategy, i.e. maximum efficiency or to the required heating capacity. The measured value is mainly the gas cooler exit temperature when optimizing the system efficiency.

- The flash gas bypass FGBV valve (1), maintains the pressure setpoint value of the separator, and the measured node is a pressure sensor connected directly to the separator.

-The suction pressure setpoints of the MT and LT compressor(s) are maintained by adjusting the frequency of the electric motors. In case of higher cooling demands, additional compressors are activated at the corresponding suction group. The measured nodes are pressure sensors connected to the dedicated suction manifolds.

-Feeding valves [V3, V4] connected to the [MT, LT] evaporators respectively are either controlled to track, superheating temperature difference values or the cabinet air temperature.

-The gas cooler bypass valve [V5] is activated if the measured gas temperature downstream the heat recovery device drops below the setpoint value.

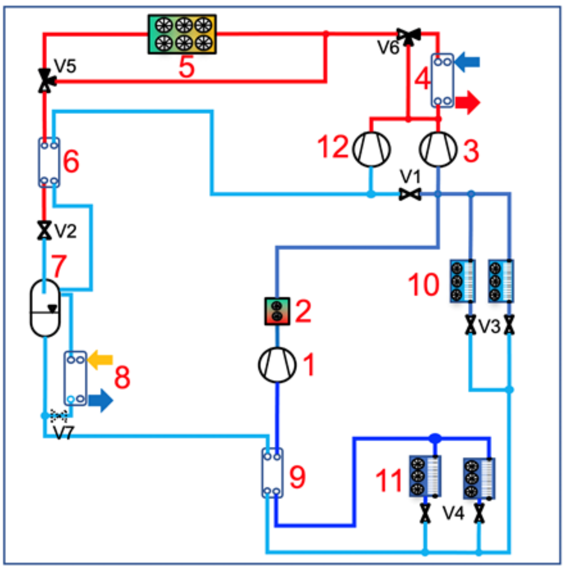
Advantages

- A simple first-generation refrigeration system, suitable for cold climates.

- System-2 “CO_2 only” Heat recovery DHW, Cooling and Refrigeration system”

This system is similar to system-1, however, with the incorporation of i) parallel compressor(s) [12] to unload the MT compressor(s) which increases the system performance, ii) dedicated AC evaporator [8], and both components are implemented to provide the building’s cooling requirements. The building's nominal design chilled water supply temperature usually ranges between 6 to 7 ˚C, hence, the parallel compressor(s)[12] which operate at higher suction pressure (36 bar) i.e compared to the MT [3] (30 bar), can satisfy the required chilled water design conditions. The refrigerant flow downstream of the MT compressor(s) [3] and parallel compressor(s) [12] flows on demand to the heat recovery device [4] before the control algorithm decides whether it is needed to reject more heat in the gas cooler [5] or bypass it through [V5]. Subsequently, the gas flow is subcooled through IHX [6], expanded through [V2] and separated / accumulated in the receiver [7] at the parallel compressor suction pressure. During low cooling requirements, the flash gas bypass valve FGBV [V1] maintains the receiver pressure as described in section XX, until the flow rate reaches the required minimum setpoint value to activate the parallel compressor. The parallel compressor by then, takes over the role of maintaining the receiver pressure level. The separated liquid flow is i) connected to the AC chiller [8] upon the cooling demand request through the On-Off valve [V7], ii) expanded through [V3] and [V4] to feed the MT and LT evaporators at their corresponding pressure levels. The leaving fluid from the LT [11] is superheated through IHX [9] before being compressed by the LT compressor(s)[1] and de-superheated [2]. Meanwhile, the gas flow leaving the MT evaporator(s) mixes with the de-superheated gas flow and the expanded flash gas through [V1] to be compressed through MT compressor(s)[3] to complete the cycle.

Table 3 System 2 - Booster with parallel compression

<table>
<tr><th></th><th>Components</th><th>Scheme</th></tr>
<tr><td>1</td><td>Low temperature compressor(s)</td><td rowspan="20">

Generalized system</td></tr>
<tr><td>2</td><td>Desuperheater (air cooled)</td></tr>
<tr><td>3</td><td>Medium temperature compressor(s)</td></tr>
<tr><td>4</td><td>Heat recovery(DHW)</td></tr>
<tr><td>5</td><td>Gascooler (air cooled)</td></tr>
<tr><td>6</td><td>Internal HX</td></tr>
<tr><td>7</td><td>Liquid separator</td></tr>
<tr><td>8</td><td>AC evaporator</td></tr>
<tr><td>9</td><td>Internal HX</td></tr>
<tr><td>10</td><td>Medium temperature evaporator(s)</td></tr>
<tr><td>11</td><td>Low temperature evaporator(s)</td></tr>
<tr><td>12</td><td>Parallel compressor(s)</td></tr>
<tr><td>--</td><td>--------------------------------------</td></tr>
<tr><td>V1</td><td>Flash gas bypass valve</td></tr>
<tr><td>V2</td><td>High pressure control valve</td></tr>
<tr><td>V3</td><td>Medium temperature evaporator(s) feed valves</td></tr>
<tr><td>V4</td><td>Low temperature evaporator(s) feed valves</td></tr>
<tr><td>V5</td><td>Bypass gas cooler valve</td></tr>
<tr><td>V6</td><td>Bypass gas heat recovery HX</td></tr>
<tr><td>V7</td><td>AC evaporator-8 on/off (optional) valve</td></tr>
</table>

PH diagram and thermodynamics analysis Figure-2

The hot gas leaving the gas cooler/condenser (thermodynamic process 5) is further subcooled through IHX [6] (thermodynamic process 6) and further expanded through the high-pressure control valve V[2].

The mixed vapor/ liquid fluid is separated (thermodynamic state 7), and the liquid flow is divided into two parallel paths. The first path is connected to the AC evaporator [8] (thermodynamic state 8), back to the separator[7] and the separated vapor is further superheated through IHX[6] (thermodynamic process 6) and compressed by the parallel compressor(s) (thermodynamic process 12). The Second path is further subcooled at the IHX [9] (thermodynamic process 9) and thereafter expanded into the medium and low temperature evaporators respectively.

The leaving saturated vapor from the LT evaporator is superheated though IHX[9] (thermodynamic process 9) before being compressed by LT compressor(s) and de-superheated (thermodynamic process 2). Further it is mixed with both the leaving saturated vapor from MT evaporator(s) and the expanded flash gas from [V1] before being compressed by the MT compressor(s) (thermodynamic process 3).

The mixed high pressure hot gas from both MT compressor(s) [3] and the parallel compressor(s) [12] is either passing through the heat recovery (thermodynamics process 4) or by passed through [V6], depending on the building heating load request, before entering the gas cooler[5] to complete the cycle.

note: the AC cooling capacity is evaluated as (the thermodynamics process 8) i.e. the enthalpy difference between (thermodynamics state7) and the saturated vapor point lies on the isobaric line of 36(bar) multiplied by the refrigerant mass flow rate entering the AC evaporator.

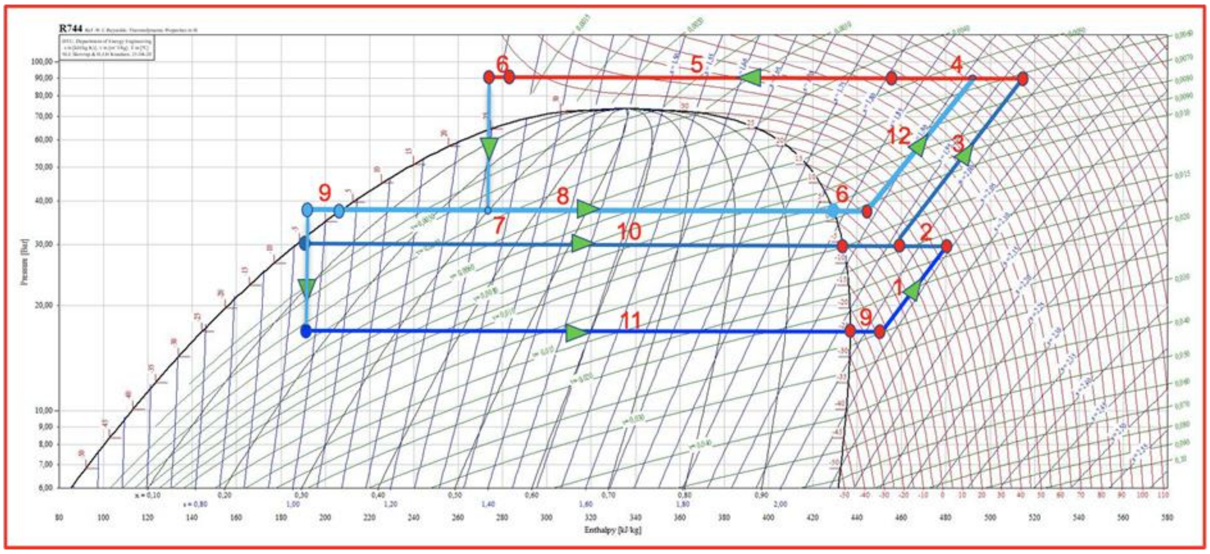


Figure 2 System-2 PH diagram

❖ **Control approach**

The control system of different components is similar to system-1 apart from:

-The control of AC evaporator-8 on/off [V7] which is switched On/Off when the measured supply to the building chilled water temperature value is higher/lower than the design setpoint value plus/minus the hysteresis value, which usually ranges between +0.5 to 1 K.

-The opening ratio of the flash gas bypass valve [V1] is evaluated as an indication of the potential flow rate through the parallel compressor, once the internally measured flow rate is larger than the compressor manufacturer recommended minimum flow rate value; the controllers outputs a Boolean true signal that switches on the parallel compressor(s).

-Staging up and down the number of active parallel compressors is mainly depending on the thermal heating and cooling demands.

Advantages

- Implementing the parallel compressor(s) presents a more integrated solution for the whole building and represents a third active temperature level, applied e.g. to integrate comfort cooling
- Higher energy savings compared to system-1
- High efficient in moderate and warm climates at elevated heat rejection temperatures.

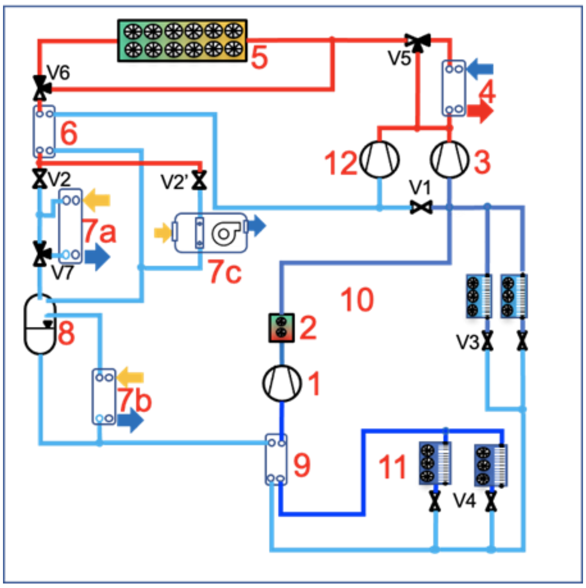
System-3 "CO_2 only" heat recovery DHW , Multiple Cooling evaporators and Refrigeration system

System-3 layout is similar to system-2 apart of indication the principle of multiple and diverse solutions for the cooling AC evaporators where three different evaporators were included (as individual examples shown in one figure).

The first evaporator is 7a; which is utilized as a water chiller, the second evaporator 7b; is a self-circulating flooded evaporator. The third 7c is a DX evaporator, where the subcooled high pressure fluid discharged from the IHX[6] is expanded through the expansion valve [V2'] upstream of the evaporator. This implementation has several advantages as it: guarantees more flexibility in the evaporator installation/location, reduces the piping heat loss, and can be utilized as an indoor air handling unit since the cooling coil is of direct expansion type.

The high-pressure (HP) gas downstream of the gas cooler[5] is subcooled through IHX[6] and diverged to be expanded through the HP control valve[V2] and the expansion valve[V2'] in case of AC demand. The vapor/liquid mixture expanded through [V2] is either flowing through the evaporator[7a] or bypassed through valve[V7] depending on the thermal cooling control system request. The flooded chiller[7b] is operated as described in system 2.

Table 4 System 3 – Booster with parallel compressor and various AC options

	Components	Scheme
1	Low temperature compressor(s)	
2	Desuperheater (air cooled)	
3	Medium temperature compressor(s)	
4	Heat recovery(DHW)	
5	Gascooler (air cooled)	
6	Internal HX	
7	7 AC evaporator's options:	
	7a controlled cooling coil	
	7b flooded evaporator	
	7c Fresh air handling unit	
8	Liquid separator	
9	Internal HX	
10	Medium temperature evaporator(s)	
11	Low temperature evaporator(s)	
12	Parallel compressor(s)	
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V1	Flash gas bypass valve	
V2	High pressure control valve	
V2'	Expansion valve	
V3	Medium temperature evaporator(s)	**Generalized system**
V4	feed valves	
V5	Low temperature evaporator(s) feed	
V6	valves	
V7	Bypass gas cooler valve	
	Bypass gas heat recovery HX	
	AC Evaporator Bypass valve	

PH diagram and thermodynamics analysis Figure-3

The refrigerant leaving the gas cooler [5] (thermodynamic process 5, identifying the high pressure) is further subcooled through IHX (thermodynamic process 6) and expanded through the high-pressure control valve to the receiver [8] pressure (thermodynamic state 8).

The vapor/ liquid mixture is separated through separator 8 and the liquid stream is divided between the AC evaporator 7b and the MT and LT evaporators. The liquid flow rate leaving the separator is subcooled at the IHX 9 and then expanded to feed ii) the MT and the iii) LT evaporators.

The leaving saturated vapor from the LT evaporator is superheated though IHX 9 (thermodynamic process 9) before being compressed by the LT compressor(s). While the leaving saturated vapor stream from MT evaporator(s) is mixed with the leaving stream from the desuperheater 2 to be drawn by the MT compressor(s) (thermodynamic process 3).

The compressed fluid then is mixed with the discharged fluid of the parallel compressors before the mixture passes (on demand) through a heat recovery heat exchanger 4 (thermodynamics process 4) to enter the gas cooler/condenser. The heat recovery process is usually implemented to generate the DHW to up to 95 ˚C, in order to utilize the high discharge temperatures if heating is needed.

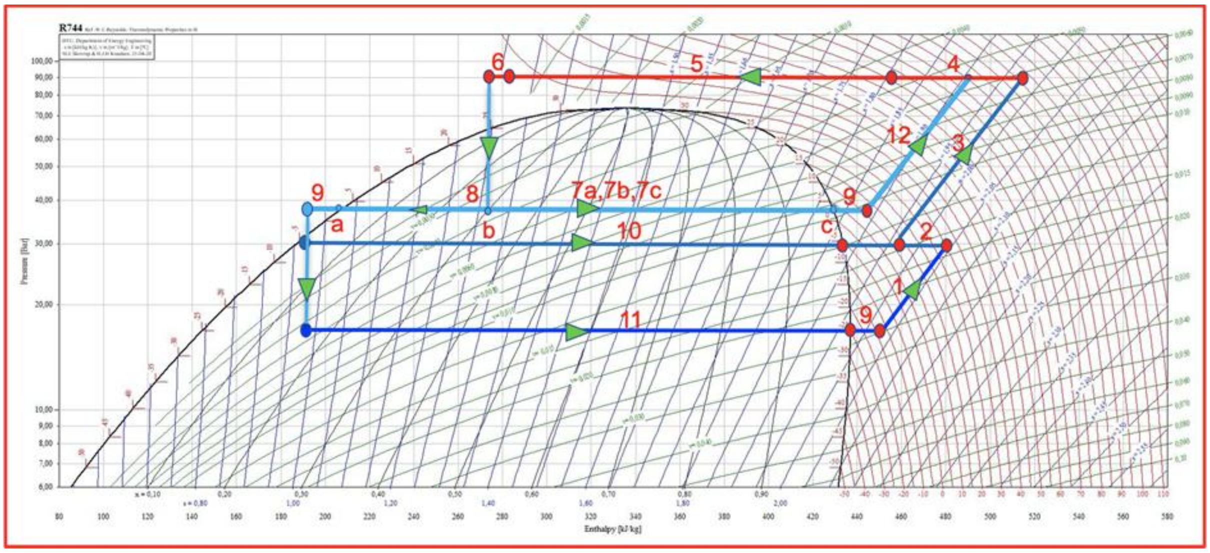


Figure 3 System-3 PH diagram

❖ **Control approach**

The control system of different components is similar to system-2 apart from:

- The DX evaporator, the R744 mass flow rate/cooling capacity and superheating temperature difference is controlled by the expansion valve [V2’] implementing a PI controller which tracks the superheating temperature difference.

- The [V2] controls the high side pressure level

Advantages

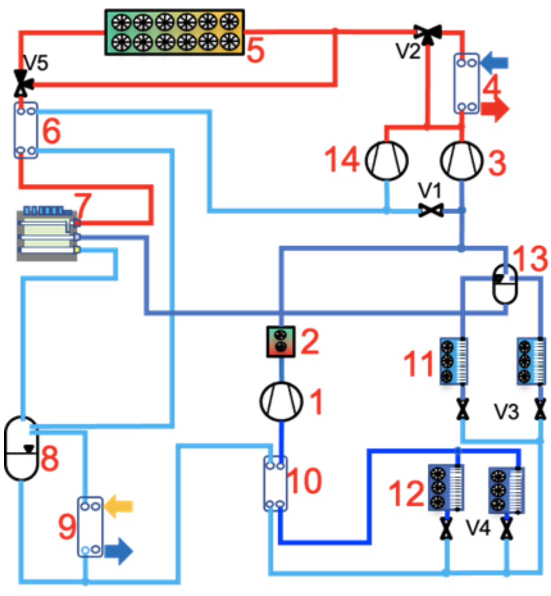
- Flexible solution with different examples on how to integrate AC evaporators that can meet building’s cooling requirements using evaporators located at both short and long paths to the machine room.

- With the multi ejectors
  - System-4 “CO_2 only” heat recovery, Cooling and Refrigeration system”

System-4 incorporates the multi-ejectors which recovers parts of the expansion work and increase the overall system efficiency . In addition, parallel compressor(s) [14] and AC evaporators / chillers [9] are integrated. Hence, this system is similar to system-3, however has an higher seasonal energy efficiency due to the expansion work utilization.

The high-pressure port of the ejector’s[7] is connected to the subcooled high pressure fluid leaving IHX[6].While, the suction pressure port is connected to the line (30bar) and fluid accumulated at the bottom level of the separator [13] and the generated exit pressure out of the ejector is typically 37bar, which represents to the receiver/separator[8] pressure level. The IHX[6] is located downstream of separator[8] where the saturated vapor leaving is superheated before being compressed through parallel compressors [14].The liquid fluid leaving receiver[8] is divided into two parallel paths, the first is connected to gravity fed AC evaporator[9] a chiller, absorbing the building cooling loads via a secondary loop and the leaving vapor is returning back into the receiver[8]. The second liquid flow rate is subcooled through IHX[10] before being expanded at [V3] and [V4] to meet the MT- and LT-refrigeration loads respectively. The saturated vapour leaving the LT-evaporators[12] is superheated through IHX[10] and compressed through LT-compressor(s)[1] before being subcooled through desuperheater[2]. Whilst the leaving saturated vapor from the MT evaporator(s) [11] is connected to the low-pressure receiver[13] collecting all fluid flows of the evaporators. The receiver outlet vapour flow meets the fluid leaving the de superheater[2] before being compressed by the MT compressor[3] to the high pressure level where it is mixed with the compressed fluid of the parallel compressor[14]. The hot vapor is either cooled through heat recovery device [4] , directly connected to the gas cooler [5] in order to complete the cycle.

Table 5 System 4 - Booster with ejector supporting the parallel compressor

	Components	Scheme
1	Low temperature compressor(s)	
2	Desuperheater (air cooled)	
3	Medium temperature compressor(s)	
4	Heat recovery(DHW)	
5	Gascooler (air cooled)	
6	Internal HX	
7	Multi Ejectors	
8	Liquid separator	
9	AC evaporator	
10	Internal HX	
11	Medium temperature evaporator(s)	
12	Low temperature evaporator(s)	
13	Liquid separator	
14	Parallel compressor(s)	
--	--------------------------------------	
V1	Flash gas bypass valve	
V2	Bypass gas heat recovery HX\Medium	
V3	temperature evaporator(s) feed valves	
V4	Low temperature evaporator(s) feed valves	
V5	Bypass gas cooler valve	**Generalized system**

PH diagram and thermodynamics analysis- Figure-4

The refrigerant leaving the gas cooler/condenser (thermodynamic process 5, identifying the high pressure) and subcooled through IHX[6] (thermodynamic process 6) is expanded and accelerated through the ejector motive nozzle and mixed with a leaving fluid from the MT evaporator due to pressure difference (thermodynamic process 7). Part of the kinetic energy of the vapor/liquid mixture is converted into a pressure increment via the diffuser where it leaves the ejector at the intermediate pressure (37 bar) (thermodynamic state 8). The vapor/liquid mixture at (thermodynamic state 8) is separated, the saturated vapor is further superheated through IHX[9] before being compressed by parallel compressor[14] (thermodynamic process 14). Whilst, the liquid fluid is subcooled through IHX[10](thermodynamic process 10) and then expanded to meet the MT[11] and LT[12] evaporators refrigeration thermal requirements (thermodynamic process 11 and 12). The saturated vapor leaving the LT evaporator is superheated through the IHX[10] before being compressed upstream of the LT(thermodynamic process 7). The hot gas leaving the LT compressor [] is de-superheated though [2] (thermodynamic process 2) before being mixed with the saturated gas leaving the MT[] and further superheated gas leaving the MT [] and through IHX[13] (thermodynamic process 13) and compressed to the HP level through compressor[3] (thermodynamic process 3). The mixed high pressure hot gas from both MT compressor(s) [3] and the parallel compressor(s) [14] is either passing through the heat recovery (thermodynamics process 4) or by passed through [V2], depending on the building heating load request, before entering the gas cooler[5] to complete the cycle.

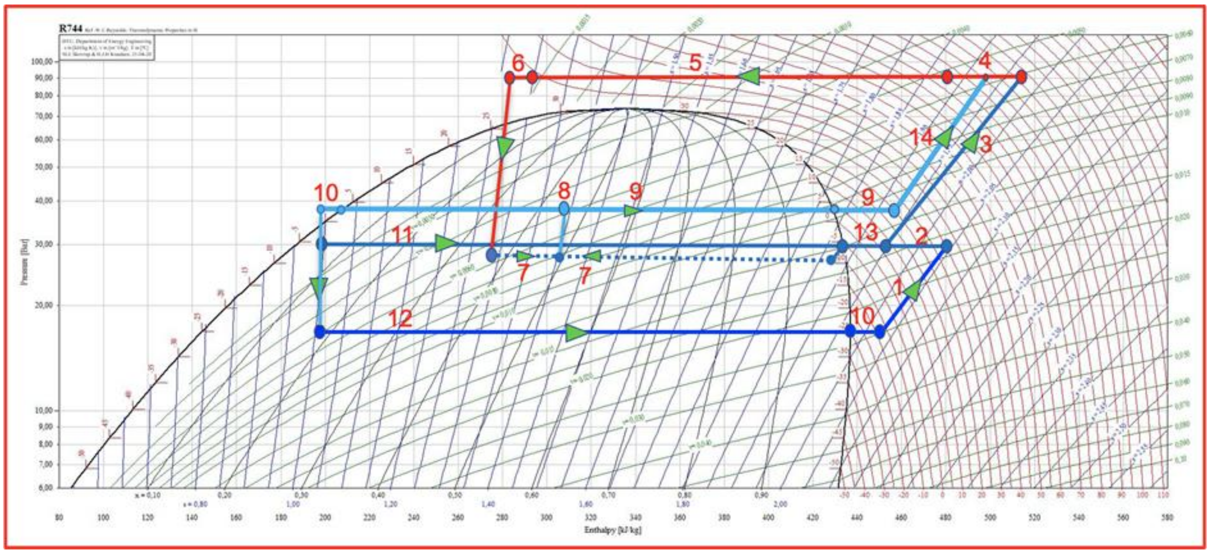


Figure 4 System-4 PH diagram

❖ **Control approach**

The main system controller typically has several PI type sub-control loops which are controlling system components i.e., valves, MT compressor(s) and LT compressor(s) and the multi ejector component.

- Valve [V2]: the PI controller. tracks the supply DHW or HW temperature and compare it t a setpoint value outputs true or false signals to flow or bypass the refrigerant fluid through the [4].

- Valve [V5]: the PI controller tracks the refrigerant gas temperature leaving the gas cooler and compare to a setpoint value and outputs true or false signals to flow or bypass the refrigerant fluid through [5].

- The multi ejectors: the PI controller tracks the high, suction and delivery pressure values and compare to setpoint and outputs true signals to one or more valves to open depending on the required capacity.

The rest of the component's controllers are clarified previously.

Advantages

- Unloading of the MT compressors which led to higher system efficiency.
- Recovery of expansion work.
- Less complicated control system since less valves are implemented.

■ System-5 "CO_2 only" heat recovery, Cooling and Refrigeration system with a dedicated ejectors for low temperature cooling requirements"

This system demonstrates a possible way of integrating a dedicated ejector for a chilled fluid circulation loop (e.g. local or district cooling loop) in addition to the commercial refrigeration cooling requirement with the previously described multi ejector. District cooling systems usually require lower supply chilled water temperature 4 to 5 ˚C and higher temperature difference 8- to 10 K or even higher compared to individual building's cooling systems and this difference is implemented to reduce the chilled water pumping work.

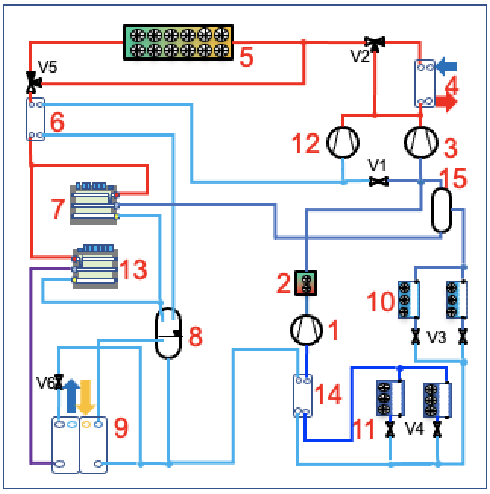
System-5 has five different pressure levels, i) high pressure gas entering the gas cooler (90 bar) HP, ii) ejectors of AC (13) and refrigeration (7) delivery pressure (~43 bar) EDP, iii) AC evaporator pressure (~37bar) ACP, iv) MT evaporators pressure (30-33bar) MP, v) LT evaporators pressure (~18 bar) LP.

In the main refrigeration circuit, the hot gas discharged from the MT and parallel compressors[3] and[12] respectively is flowing on demand to the heat recovery device[4] otherwise toward either, the gas cooler[5] through [V2] or IHX [6] though [V]5 depending on the system valves control characteristics.

The high pressure gas is subcooled through the internal heat exchanger[6] before entering the multi ejector's high pressure port[7], the suction port is connected to the low pressure receiver[15] and the discharge port is connected separator[8]. The liquid leaving the separator[8] is supplied to the MT and LT evaporators[10&11] through the electronic valves [V3] and [V4]. Downstream of LT evaporator[11] the gas is superheated through an IHX[14] before being compressed and de-superheated through[1] and [2] respectively. While downstream of the MT evaporators [10], the low-pressure receiver[15] collects the outlets of the MT-evaporators. Depending on the ejector performance, a part of the vapour is returned to the separator via the ejectors while the remaining amount is compressed by the MT compressors. Before compression, the remaining vapour flow rate of the low-pressure receiver is mixed with the flow rate of the flash gas bypass valve and the de-superheated gas of the LT section.

In the cooling circuit, the AC evaporator(9) to cool a secondary fluid is a two-circuit/stage heat exchanger. The first circuit, gravity fed, is connected with the liquid refrigerant leaving the liquid separator[8] at the bottom, vapour returns back to the separator. The first circuit is pre-cooling the fluid of the secondary cooling loop . The second refrigeration circuit is connected to the liquid fluid the separator (8) and an expansion valve V6 in between, enabling a new temperature pressure level, ACP. The secondary cooling loop fluid is further cooled at lower evaporation pressures provided by the AC ejector [13]. The vapour is compressed by the AC ejector[13] to the pressure level of the separator[8] before entering the suction port of the parallel compressors(12). To secure a superheated compressor inlet condition, the saturated vapour leaving the top of separator[8] is further superheated through IHX[6] before being compressed through compressor[12]. The flash gas bypass valve FGBV [V1] secures the separator's pressure level by throttling a dedicated amount of vapor towards the MT suction port in case the parallel compressor[12] is not active.

Table 6 System 5 - Booster with ejector supporting the parallel compressor and low-pressure lift ejector for advanced AC

	Components	Scheme
1	Low temperature compressor(s)	
2	Desuperheater (air cooled)	
3	Medium temperature compressor(s)	
4	Heat recovery	
5	Gas cooler (air cooled)	
6	Internal HX	
7	Multi Ejectors	
8	Liquid separator	
9	AC evaporator	
10	Medium temperature evaporator(s)	
11	Low temperature evaporator(s)	
12	Parallel compressor(s)	
13	Multi Ejectors	
14	Internal HX	
15	Liquid separator	
--	--------------------------------------	
V1	Flash gas bypass valve	
V2	High pressure control valve	
V3	Medium temperature evaporator(s) feed valves	
V4	Low temperature evaporator(s) feed valves	
V5	Bypass gas cooler valve	
V6	AC Evaporator feed valve	**Generalized system**

PH diagram and thermodynamics analysis Figure-5

The refrigerant leaving the gas cooler (thermodynamic process 5, identifying the high pressure) is further subcooled (thermodynamic process 6). Part of the fluid is expanded and accelerated through the AC ejector motive nozzle and mixed with the leaving saturated vapor from the AC evaporator circuit-2 (thermodynamic process 13) to subsequently pre-compressed to the vapor/liquid mixture (thermodynamic state 8). While the rest of the high-pressure refrigeration fluid is expanded and accelerated through the refrigeration ejectors and mixed with the saturated vapor leaving the MT evaporator (thermodynamic process 7). The mixture is pre-compressed to (thermodynamics state 8) to be mixed again with the delivery fluid leaving the AC ejectors.

The vapor/liquid mixture at (thermodynamic state 8). is separated into saturated vapor which is further superheated (thermodynamics state 6) and compressed (thermodynamics state 12) and saturated liquid which is divided into three paths,

i) connected to AC evaporator circuit1[9] to meet the building cooling load at the EPD level,

ii) expanded to the ACP level AC evaporator circuit2[9]to meet the district cooling's requirement (thermodynamic process 9),

iii) further subcooled (thermodynamics process 14) and subsequently expanded to MP (thermodynamics process 10) and LP (thermodynamics process 11) to meet the refrigeration requirements.

The saturated vapor leaving the LT evaporators is further superheated (thermodynamics process 14) before being compressed (thermodynamics process1) and de-superheated (thermodynamics process 2). While the saturated vapor leaving the MT evaporators is further superheated (thermodynamics process 15) and mixed with the fluid leaving the de-superheater[2] before being compressed to the HP level (thermodynamics process 3) and mixed with the HP gas leaving compressor[12]. The heat recovery process for different purposes is executed through (thermodynamics process 4) before entering again into the gas cooler to complete the cycle.

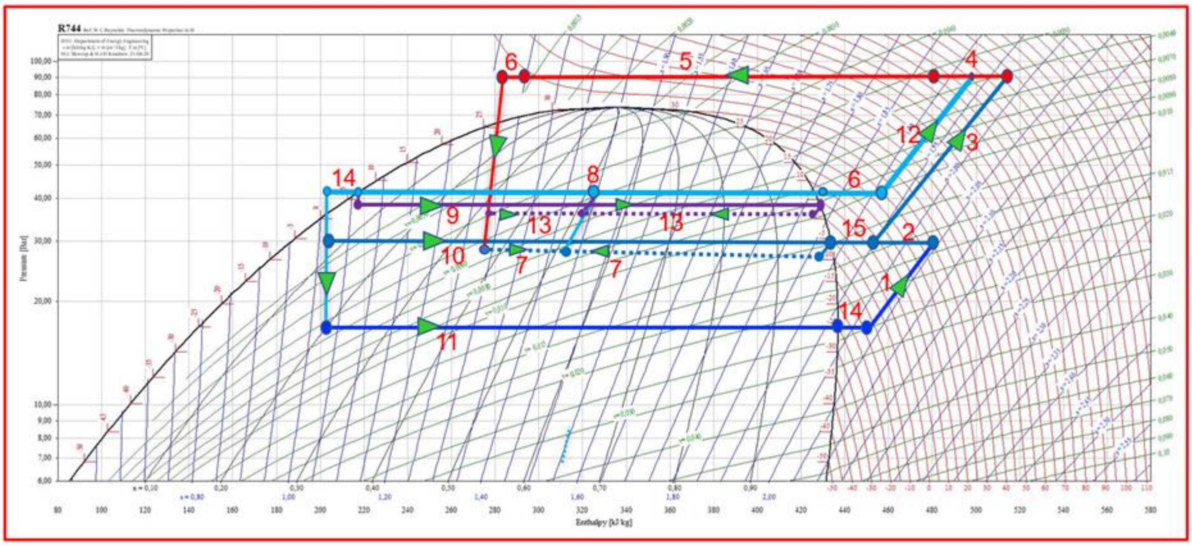


Figure 5 System-5 PH diagram

❖ **Control approach**

The control concept of different components is similar to the previously explained system4, apart from:

- The AC evaporator feeding valve[V6] where the PI controller tracks the measured chilled water supply temperature and compare it to the design setpoint value and outputs the valve opening ratio.

Advantages

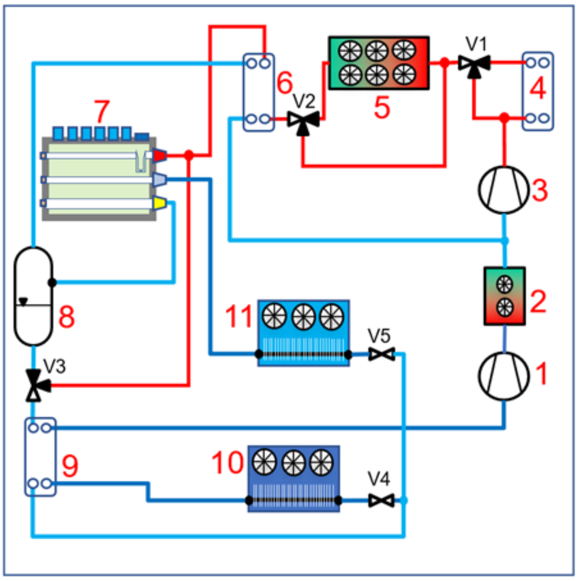
- A more flexible system that could cover the building or district cooling requirements in addition to the refrigeration systems.

■

System-6 “CO_2 only” Two mode Ejector Refrigeration system

This system demonstrates a simple and efficient solution to function in modes (winter/passive or summer/active) by switching the operating mode of a multi-ejector[7] between passive and active. The control system decides the high side pressure level (subcritical or transcritical) depending on the ambient temperatures and energy demand of the building. The summer/active and winter/passive modes descriptions are clarified in detail below.

Table 7 System 6 – Simple Booster with ejector in active and passive mode

	Components	Scheme
1	Low temperature compressor(s)	 Generalized system
2	Desuperheater (air cooled)	
3	Medium temperature compressor(s)	
4	Heat recovery	
5	Gas-cooler (air cooled)	
6	Internal heat exchanger	
7	Multi Ejector / high pressure control device	
8	Liquid separator	
9	Liquid subcooler	
10	Low temperature evaporator(s)	
11	Medium temperature evaporator(s)	
--	-------------------------------------	
V1	Bypass heat recovery	
V2	Bypass gascooler	
V3	Mode switch: Ejector on/off mode	
V4	LT Evaporator Feeding Valve	
V5	MT Evaporator Feeding Valve	

Summer mode-active ejector “Transcritical operation”

During the summer mode the multi-ejector is active and the port of valve[V3] connected to the high-pressure side is closed. The high pressure gas discharged from the gas-cooler[5] is further subcooled through IHX[6] and connected to the high side pressure port of the multi-ejector[7].

The multi-ejector’s suction port is connected to the saturated vapor line leaving all the MT evaporator(s)[11] while the ejector discharge port is connected directly to the receiver[8]. The saturated liquid leaving the receiver[8] is further subcooled through the IHX[9] and subsequently expanded to MT[11] and LT[10] pressure levels through [V5] and [V4] respectively to meet the refrigeration requirements. The saturated vapor leaving the LT evaporator [10] is further superheated through IHX[9] before being compressed and de-superheated through [1] and [2] respectively. The saturated vapor leaving the top level of receiver[8] is further superheated through IHX[6] before being mixed with the fluid from the LT-side, which leavs the desuperheater[2], and compressed through MT compressor[3]. The high-pressure discharge gas leaving compressor[3] flows on demand into the heat recovery device[4] or bypassed through [V1] towards either the gas cooler[5] or in case of high heating demands in the building directly bypassing the exterior gas-cooler though [V2] to IHX[6] in order to complete the cycle.

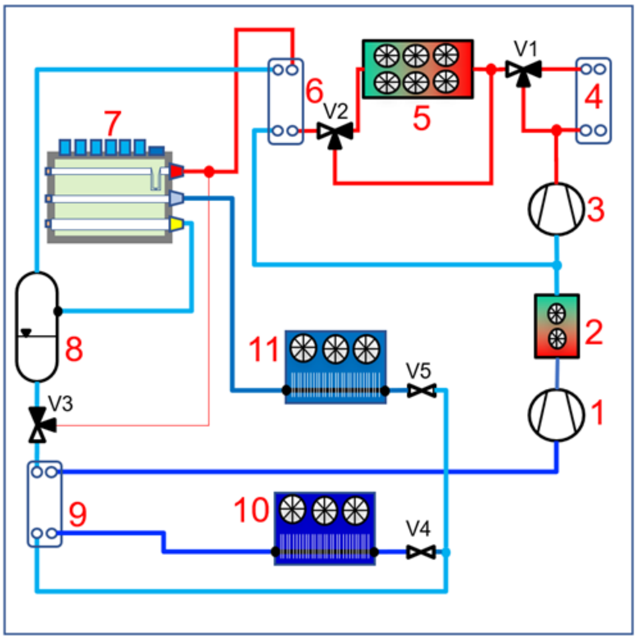


Figure 6 System 6 Summer mode - transcritical operation

PH diagram and thermodynamics analysis Figure-7

The refrigerant discharged from the gas cooler (thermodynamic process 5, identifying the high pressure) and subcooled (thermodynamic process 6) is expanded and accelerated through the ejector motive nozzle and mixed with the saturated vapor leaving the MT evaporator due to pressure difference (thermodynamic process 7). Part of the mixture kinetic energy is converted into a pressure increment via the diffuser where the mixture leaves the ejector at the intermediate pressure (40 bar) (thermodynamic state 8).The vapor liquid mixture at (thermodynamic state 8) is separated and the saturated vapor is further superheated at IHX [6]. While the saturated liquid is subcooled (thermodynamic process 9) and subsequently expanded to meet the LT and MT evaporators refrigeration thermal requirements (thermodynamic process 10 and 11). The saturated vapor leaving the LT evaporator is further superheated (thermodynamic process 9) before being compressed (thermodynamic process1), de-superheated(thermodynamic process2) and mixed with the superheated vapor fluid discharged from the top of the receiver[8](thermodynamic process6). The mixture is then compressed (thermodynamic process3) and flows to either the heat recovery device(thermodynamic process4) or bypassed to the gas cooler(thermodynamic process5) to complete the cycle

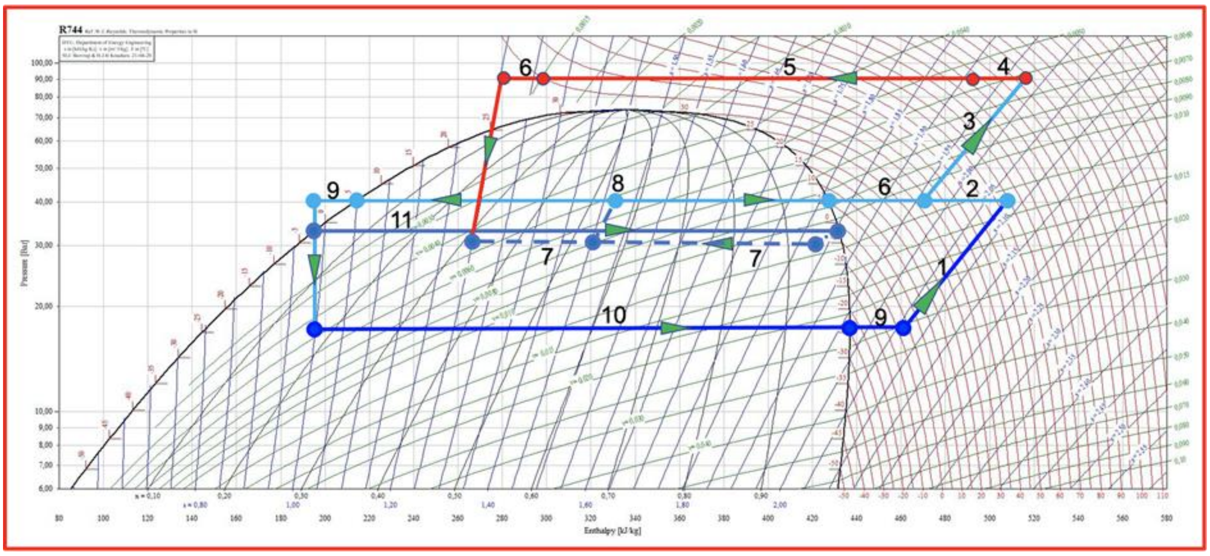


Figure 7 System-6 Summer mode PH diagram

❖ **Control approach**

The main system controller typically has several PI type sub-control loops which are controlling system components i.e., valves, MT compressor(s) and LT compressor(s) and the multi ejectors.

- Three way valve [V3] he PI controller tracks the ambient temperature and compare it to a setpoint value.

During summer season the controller outputs a Boolean true signal to open the valve's [V3] port connected to the bottom of the receiver and a Boolean false signal to close the valve's [V3] port connected to high pressure side.

- The multi ejectors PI controller tracks the measured pressure values at the high, suction and delivery pressure ports, compare it to the setpoint values and outputs the valves opening ratios depending on the required capacity.

- The control approach of the rest of the components have been clarified previously.

Winter mode-passive ejector "subcritical operation"

During the winter season, the multi-ejector[7] is passive, meaning no expansion nor precompression processes are occurring and it is only used to connect the saturated vapor leaving the MT towards the low pressure receiver[8].

The system operates in the subcritical region where the high-pressure value is as low as 55 bar, and the outlet port of valve[V3] is connected to the port towards the high-pressure side, while the port connected to the bottom of the separator is closed. The condensed fluid leaving the gas cooler (condenser)[5] is slightly subcooled through IHX[6] followed by another subcooling process through IHX[9] and subsequently expanded through the electronic feed valves [V4] and [V5] to meet the MT[11] and LT [10] evaporators refrigeration requirements. The main controller must arrange the opening degree of all the evaporator feeding valves [V4 & V5] and the condenser performance to maintain the minimum high side pressure. The saturated vapor leaving the LT evaporators is superheated through IHX[9] before being compressed and de-superheated at [1]and [2] respectively. While the saturated vapor leaving the top of the receiver [8] is further superheated though IHX[6] before being mixed with the fluid leaving the desuperheater[2] and compressed through[3].The heat recovery device performance is limited when the system operates at subcritical conditions. However, if more heating is required in the building, the high side pressure can be adjusted and operation in the transcritical region (= active ejector mode) is possible, accordingly the exterior gas-cooler[5] is then bypassed and IHX[6] to completes the cycle.

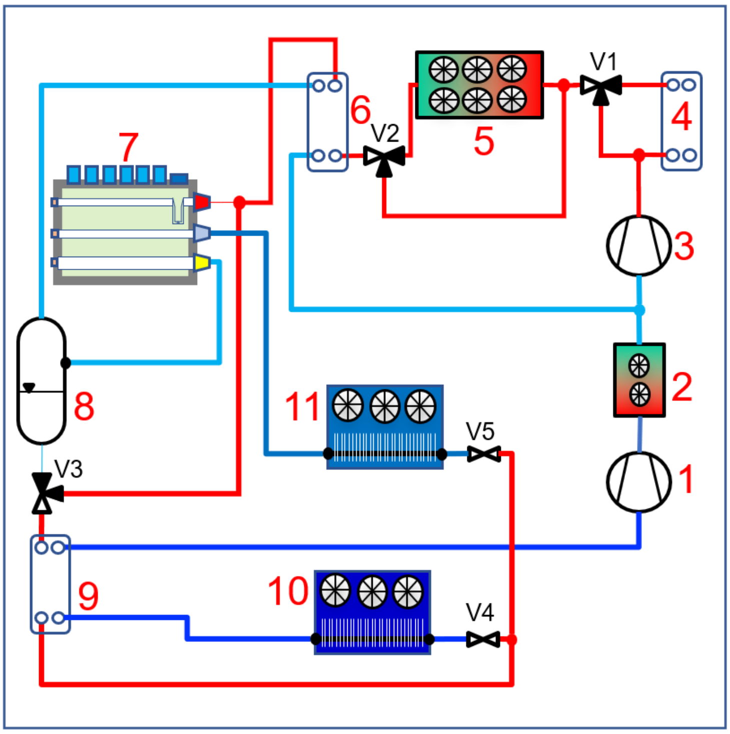


Figure 8 System 6 Winter Mode - subcritical operation

PH diagram and thermodynamics analysis Figure-9

The refrigerant leaving the gas cooler (thermodynamic process 5, identifying the high-pressure HP) is subcooled first through IHX [6] and followed by IHX [9] (thermodynamic process 6 and 9) then expanded through [V5] and [V4] to meet the MT and LT evaporators refrigeration requirements (thermodynamics process 11 and 10) respectively.

The saturated vapor leaving the LT evaporator(s) is superheated (thermodynamics process 9) before being compressed (thermodynamics process 1) and subsequently de-superheated (thermodynamics process2).

While the saturated vapor leaving the MT evaporator passes through the “passive ejector” to the liquid separator (thermodynamics state 8). The saturated vapor leaving the separator then is superheated (thermodynamics process 6) before being mixed with the de-superheated vapor downstream of [2](thermodynamics process 2). The mixture is compressed to the HP level (thermodynamics process 3). The heat recovery process for different purposes is executed through (thermodynamics process 4) before entering again into the gas cooler to complete the cycle.

It is worth mentioning that the MT evaporator pressure is slightly higher than the receiver pressure value due to the multi ejector's minor pressure drop.

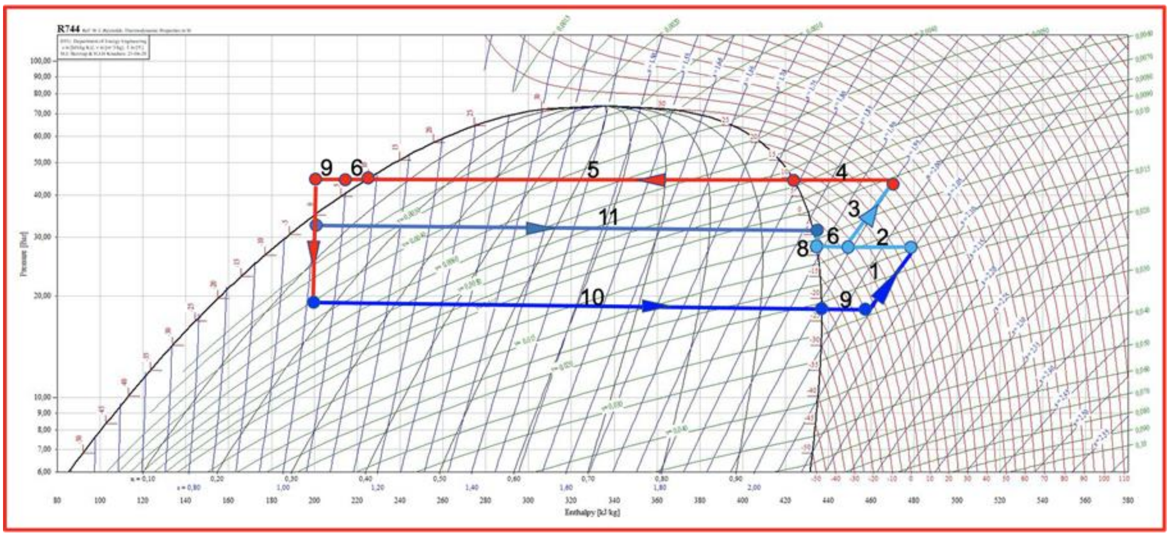


Figure 9 System-6 Winter mode PH diagram

❖ **Control approach**

-Three way valve [V3]: the PI controller tracks the ambient temperature and compare it to a setpoint value. During the winter season the controller outputs a Boolean false signal to close the valve's [V3] port connected to the bottom of the receiver and a Boolean true signal to open the valve's [V3] port connected to high pressure side.

-The multi ejector's: the PI controller signal is overridden by a supervisor controller which outputs a Boolean false signal to close the high pressure connected valve and a Boolean true signal to fully open both the suction and delivery valves.

-The control approach of the components has been clarified previously.

Advantages

- More efficient system i.e. energy savings wise, since it can switch from transcritical to subcritical based on the climate conditions.

■ System-7 “CO_2 only” Reversible heatpump fully integrated solution; Heating, DHW, Cooling and Refrigeration system

This system demonstrates an integrated solution to provide for the building’s cooling or heating thermal requirements in addition to commercial refrigeration and DHW demands. The system has an advanced layout where the building’s thermal heating/cooling cycle is integrated in parallel to the operation required for the commercial refrigeration cycle, where the:

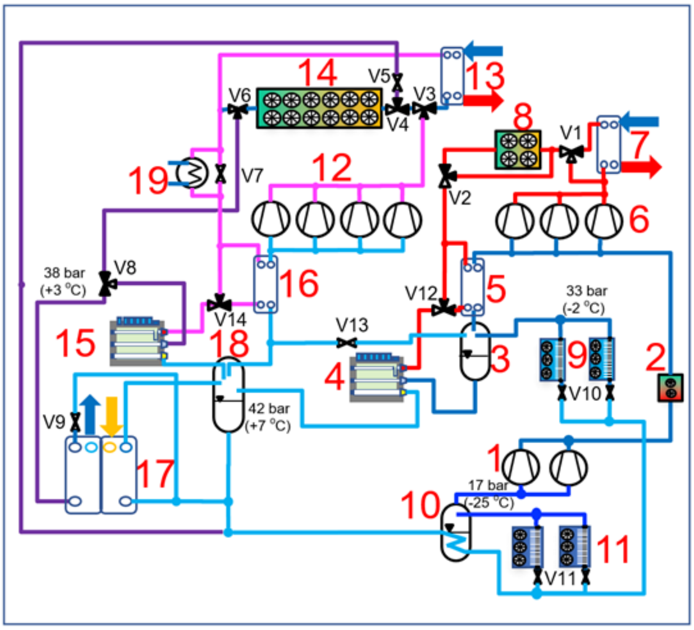
i) **Building thermal heating and cooling cycle components’** includes: a reversible heat pump heat exchangers [14,17], a dedicated low pressure lift (high entrainment) multi-ejector[15], AC/HP compressor(s) [12], heat recovery device [13], and the

ii) **Refrigeration cycle components’ includes**: MT- and LT-evaporators [9], [11], MT- and LT-compressors [1], [6], a dedicated high pressure lift multi-ejector for refrigeration [4], heat recovery device [7] and gas cooler[8].

The system´s supervisory controller switches between the summer and winter modes by controlling the status {open or close} of valves [V3, V4, V5 and V8] depending on the building thermal requests and the ambient temperature. The detailed description of the summer and winter modes are clarified below.

Table 8 System 7 – Booster with multiple heat pump and AC functions

	Components	Scheme
1	Low temperature compressor(s)	
2	Desuperheater (air cooled)	
3	Liquid separator	
4	Multi Ejector / high pressure control	
5	Internal heat exchanger	
6	Medium temperature compressor(s)	
7	Heat recovery (DHW)	
8	Gascooler (air cooled)	
9	Medium temperature evaporator(s)	
10	Liquid subcooler / receiver	
11	Low temperature evaporator(s)	
12	AC compressor(s)	
13	Heat recovery (heating mode)	
14	Exterior HX (AC mode:gas cooler, heatpump mode: Evaporator)	
15	Multi Ejector / HeatPump-AC	
16	Internal heat exchanger	
17	Chiller evaporator {double HX circuits}	
18	Liquid separator	
--	-------------------------------------	
V1	Bypass heat recovery DHW (7)	
V2	Bypass gascooler(8)	
V3	Bypass heat recovery (13)	
V4	Bypass gas cooler (14)	
V5	Expansion valve for heat pump mode	
V6	Heat pump reverse cycle control valve	
V7	Bypass heat recovery (19)	
V8	Heat pump reverse cycle control valve	
V9	Expansion valve chiller evaporator	
V10	MT Evaporator Feeding Valve	
V12	LT Evaporator Feeding Valve	
V13	ByPass internal HX(5)	
V14	Flash gas bypass valve	
V15	ByPass internal HX(16)	



Generalized system

Summer mode operation

During the summer mode and for the **building´s cooling cycle**, the high pressure gas discharged from the AC compressor[12] bypasses the heat recovery device[13] and enters the gas cooler[14] where heat is rejected to the ambient. Further heat rejection may take place in an auxiliary subcooler[19] prior the IHX [16] or the high pressure fluid is directly entering the AC ejector´s [15]high pressure port, while its discharge port is connected to the main separator [18].

The accumulated liquid fluid at the bottom of the separator [18] is:

i) connected to the first (out of two) heat exchangers, operating in a gravity feeding mode. The first evaporator of the two stage AC evaporator [17] is the pre-cooler, receiving the returning secondary loop liquid at the highest temperature level, to absorb a part of the building cooling demands, enabling elevated evaporation temperatures. The outlet of the first evaporator circuit is connected to the upper part of the separator [18],

ii) in the second part of the evaporate, the liquid refrigerant is expanded through [V9] to provide the second stage of secondary fluid cooling at lower temperature levels. Due to the precompression of the ejector, i.e. chilled water supply temperature of {~5C} can be provided, while the vapour leaves the unit towards the suction port of the AC ejector[15] through via the valve[V8],

iii) further subcooled through the integrated liquid sub-cooler[10] and subsequently connected to the LT-[11] and MT- [9]evaporators through feeding valves [V11, 10].

The saturated vapor leaving the top of receiver [18] is further superheated through IHX[16] before being compressed by the parallel compressors[12] to complete the building cooling cycle.

While for the **refrigeration cycle**, the fluid leaving the LT evaporator [11] is collected in the low pressure receiver with the integrated sub-cooler[10] before being compressed and de-superheated through [1] and [2] respectively and connected to the separator[3]. Likewise for the saturated vapor leaving the MT evaporator(s). The amount of fluid which is drawn by the high pressure lift ejector[4] and delivered to the separator[18] depends on the available expansion work. The remaining saturated vapor leaving the separator[3] is further superheated through IHX [5] before being compressed through he MT compressors[6]. The discharged HP gas is either directed to the heat recovery unit[7] or bypassed through [V1] towards the gas cooler. The HP gas is either subcooled through IHX[5], enabling a superheat adjustment or in case of 100% bypass, directly connected to the high pressure lift multi-ejector(4) high pressure port.

The flash gas bypass valve [V13], maintains the separator[18] pressure level by expanding a dedicated amount of vapor towards separator[3] in case the parallel compressor[12] is not in operation.

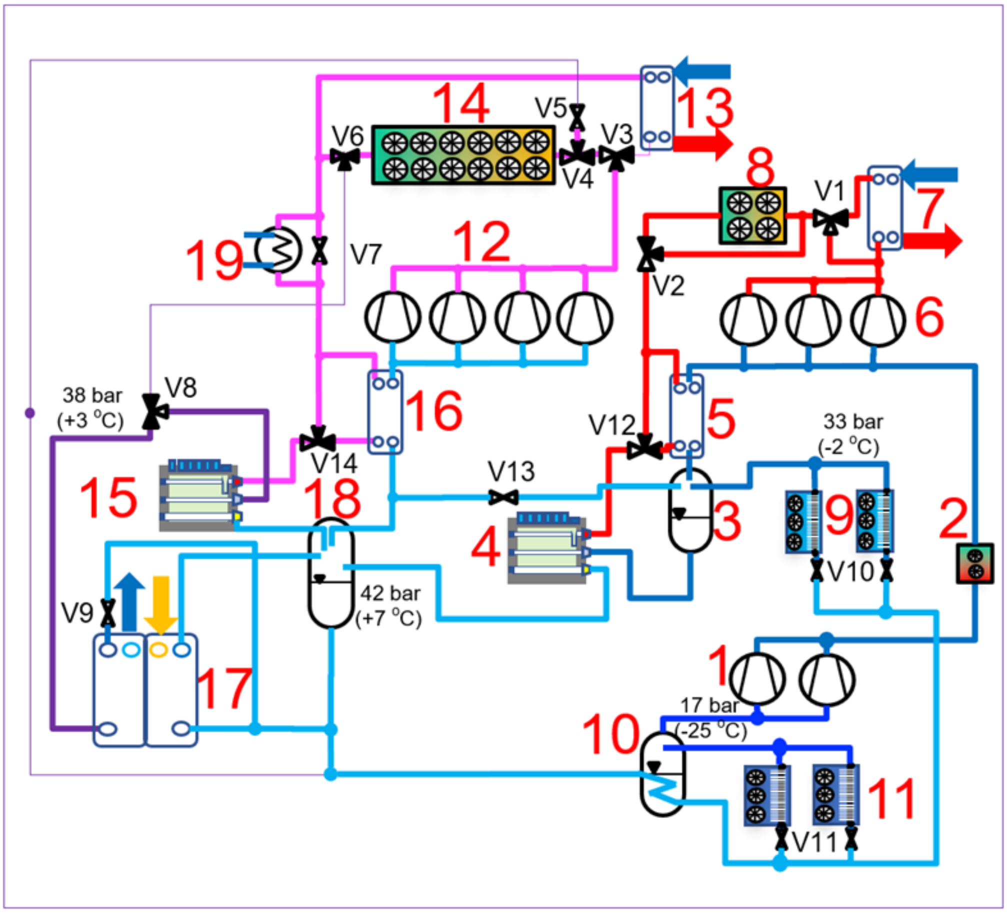


Figure 10 System 7 Summer mode operation

PH diagram and thermodynamics analysis Figure-11

- **Building cooling cycle**

The refrigerant leaving the gas cooler (thermodynamic process 14, identifying the high-pressure HP) is further subcooled (thermodynamic process 16) and subsequently expanded and accelerated through (AC multi ejectors component) mixed with the saturated vapor leaving the AC evaporator (thermodynamics process 15).and pre-compressed through ejector diffuser (thermodynamics state 18). The vapor liquid mixture is separated, part of the saturated liquid fluid is expanded to the second circuit of the AC evaporator pressure level to meet the second circuit cooling requirement's (thermodynamics process 17) and the other section is further subcooled (thermodynamics process 10) and connected to the refrigeration system. While the separated vapor is further superheated (thermodynamics process 16) before being compressed (thermodynamics process 12) and connected to the gas cooler to complete the AC system cycle.

- **Refrigeration cycle**

The subcooled liquid (thermodynamics process 10) is subsequently expanded to the MT and LT pressure levels (thermodynamics process 9, 11) respectively. The saturated vapor leaving the LT evaporator is further superheated (thermodynamics process 10) before being compressed (thermodynamics process 1) and subsequently de-superheated (thermodynamics process 2). While the saturated vapor leaving the MT is connected to [3] and further superheated (thermodynamics process 5) before being mixed with the de superheated fluid leaving [2] and compressed (thermodynamics process 6). While the hot recovery device is activated, the hot gas is cooled (thermodynamics process 7) and subsequently cooled (thermodynamics process 8) and (thermodynamics process 5) to be expanded, mixed with the saturated vapor leaving separator[3] (thermodynamics process 4) and pre-compressed to (thermodynamics state 8) to complete the cycle.

❖ Control approach

The main system controller typically has several PI type sub-control loops which are controlling system components i.e., valves, MT compressor(s) and LT compressor(s) and the multi ejectors and logical controllers which decides the status [open, close} of different valves. During summer season,

-Two way valve [V5] is closed

-Three way valve [V3] with the port connected to HX [13] and the valve [V6] with the port connected to [V8] are closed.

-The status of valve [V7] is determined based on the optional thermal service request gas cooler and

-The status of valve [V14] is determined based on the gas cooler´s refrigerant leaving temperature and AC compressor´s refrigerant suction temperature.

-The control approach of the rest of components have been clarified previously.

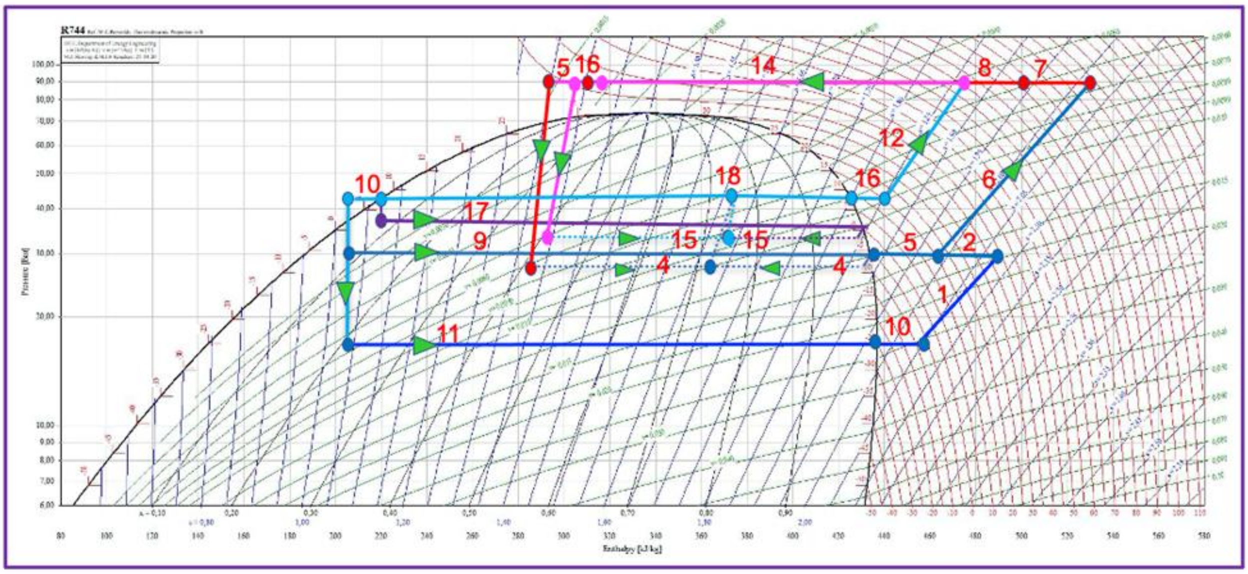


Figure 11 System-7 Summer mode PH diagram

Winter mode operation

Building heating cycle

During the winter mode, the heat pump reverses its operation where the exterior heat exchanger[14] operates as an evaporator, while the AC evaporator [17] is typically not utilized and therefore in this example isolated from the circuit by switching off the valve [V8]'s port connected to the AC evaporator. The valves [V3],[V5] are switched on, in addition to the valve´s [V6] port connected to [V8].The HP gas leaving the heat recovery[13]downstream of the parallel compressors[12] is further subcooled through IHX[16] before being connected to the heat pump ejector´s [15]HP port through [V14]. While the suction port is connected to the saturated vapor leaving [14] through [V8] while, the delivery pressure port is connected to the separator [18].

Refrigeration cycle

The separated liquid at [18] is further subcooled through[10] and subsequently expanded to MT and LT evaporators pressure level to meet the required refrigeration loads. The leaving saturated vapor from [11] is superheated through [10] before being compressed and de-superheated through [1] and [2] respectively. While the saturated vapor leaving the MT is connected to the separator[3]. The saturated vapor form [3] is superheated through IHX[5] before being mixed with the de-superheated fluid leaving [2] and subsequently compressed through[6]. The HP hot gas flows on demand through the heat recovery device [7] and further subcooled through [8] and IHX[5]. The subcooled HP gas is connected to the refrigeration multi ejectors[4] hP port, while its suction port is connected to [3] and the delivery port is connected to [18] to complete the cycle.

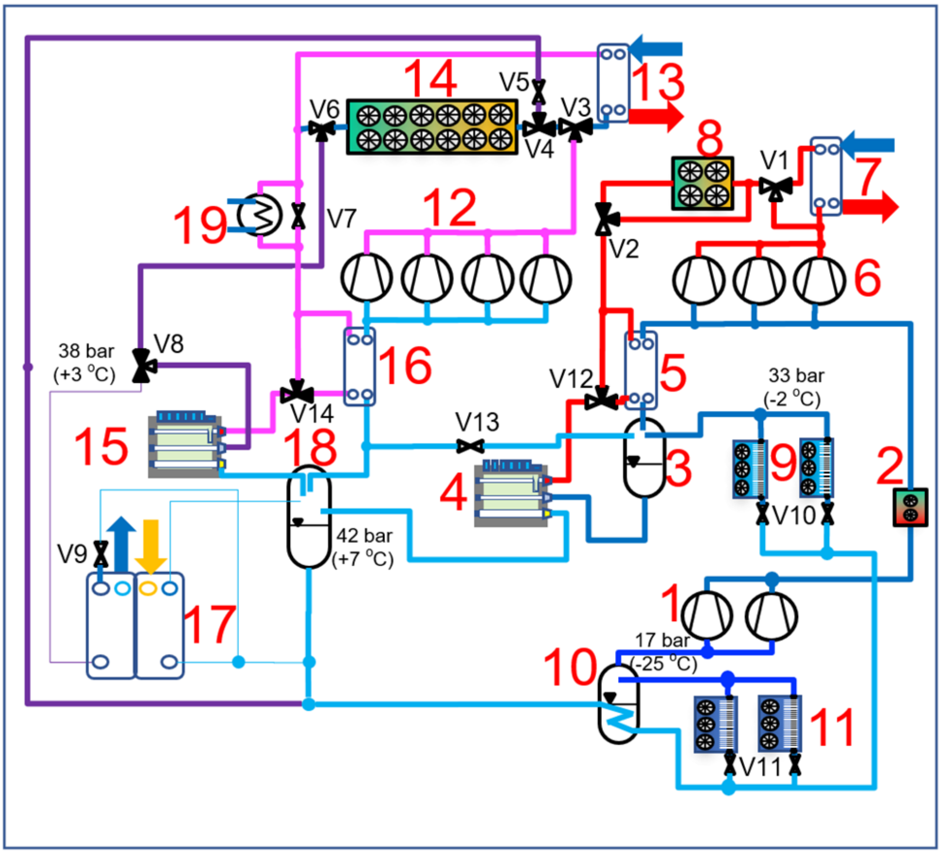


Figure 12 System 7 Winter mode operation

PH diagram and thermodynamics analysis Figure-13

- **Building heating cycle**

The refrigerant leaving the HX [13] (thermodynamic process 13, identifying the high pressure HP) is further subcooled through IHX [16] (thermodynamic process 16). Expanded and accelerated through (AC multi ejectors component) mixed with the leaving saturated vapor leaving the gas cooler [14] i.e reversible heat pump evaporator and pre-compressed through ejector diffuser to thermodynamics state 18 and pressure of (42 bar). The vapor liquid mixture is separated at separator [18], the saturated liquid stream is expanded to the gas cooler [14] pressure level at (38 bar) while the saturated vapor stream is subcooled through IHX [16] (thermodynamics process16) before being compressed (thermodynamics process 12) to complete the cycle.

- **Refrigeration cycle**
- The refrigeration cycle thermodynamic description is exactly as the summer mode operation.

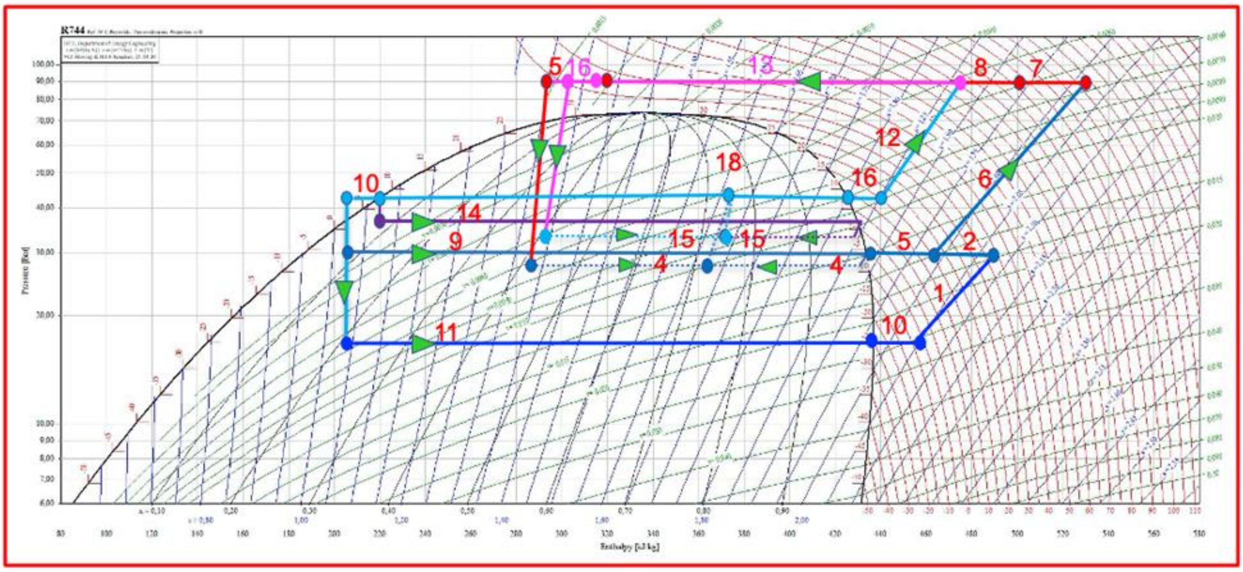


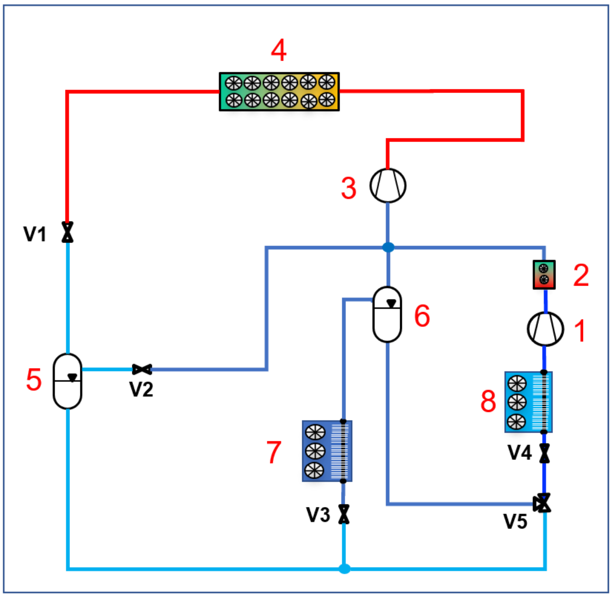
Figure 13 System-7 Winter mode PH diagram

provide for higher operational COP and energy efficiency for applications as Hotels.

System-8 “CO_2 only” No expansion work recovery - FTE

This system demonstrates the working of FTE transcritical CO_2 system by EPTA, a modified baseline booster system without expansion work recovery. Hot gas discharged from the MT compressor(s) [3] flows straight towards the gas cooler[4]. The refrigerant exit temperature from the gas cooler is a function of its size and the ambient temperature. The high-pressure gas expands through the high-pressure control valve [V1]. Downstream of high-pressure control valve the two-phase fluid is separated. The liquid exits from the lower part of the separator [5] towards the MT and LT evaporators. The electronic valves [V3] and [V4] are the refrigerant feeding valves for the evaporators to maintain the setpoint values (air temperature inside the cabinets). Downstream of the medium temperature evaporators, a low pressure receiver[6] enables the MT-evaporator control the operate these heat exchangers always without superheating the fluid. The remaining liquid is collected in the low pressure receiver[6]. When a certain amount of liquid is accumulated, the supply of liquid towards the LT-evaporators [8] changes by the position of the valve[5] from the separator to the low pressure receiver, based on a level signal inside the low pressure receiver. Downstream of the LT evaporators [8], the vapor is compressed by the LT compressor(s)[1]. Hot gas discharged from the low temperature compressor(s) [1] flows into the desuperheater [2] device to reduce the temperature of the fluid prior mixing. Prior compression by MT compressors[3], the suction flow is mixed with the flash gas bypass flow downstream of the separator [5], along with the vapor from MT evaporators leaving the low pressure receiver[6] and the de-superheated flow from the LT side.

Table 9 System 8 – Simple Booster with flooded MT evaporators

	Components	Scheme
1	Low temperature compressor(s)	
2	Desuperheater	
3	Medium temp. compressor(s)	
4	Gas cooler	
5	Liquid separator	
6	Low pressure receiver	
7	Medium temp. evaporator(s)	
8	Low temp. evaporator(s)	
--	--------------------------------------	
V1	High pressure control valve	
V2	Flash gas bypass valve	
V3	Medium temp. evaporator(s) feed valves	
V4	Low temp. evaporator(s) feed valves	
V5	Liquid supply valve for LT (from 5 or 6, depending on liquid level inside 6)	**Generalized system**

PH diagram and thermodynamics analysis -Figure-14

Case-1

The refrigerant leaving the gas cooler/condenser (thermodynamic state 4, identifying the high-pressure HP) is expanded through the high-pressure control valve (thermodynamic state 5). The mixed vapor/ liquid stream is separated and expanded into the medium and low temperature evaporators at stage [7] and [8] respectively. Liquid is only supplied towards the evaporators from the separator.

The fluid leaving the separator is expanded and passes through the low temperature evaporator (thermodynamics process 8). The two-phase fluid out of the medium temperature evaporator is separated inside the low-pressure receiver. Vapour flows towards the compressors, while the liquid is stored and supplied to the LT evaporators as described for case 2.

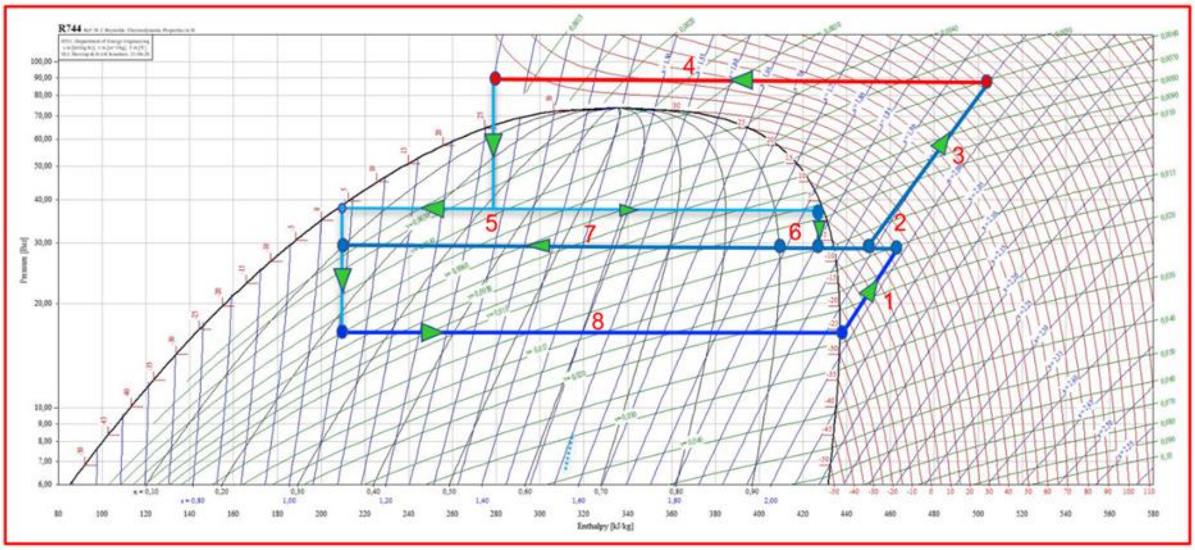


Figure 14 System-8 PH diagram (Case-1)

- ❖ **Control approach**

The control concept of different components is similar to the previously explained systems.

The supervisory controller guarantees the optimum system operation by switching the activation Boolean True signal of [V5]. A level sensor is measuring the liquid level inside the low pressure receiver[6], sends the measured value to the controller where it adds the hysteresis value and compare it to the setpoint value.

In Case1, when the liquid level is below the setpoint+ hysteresis value, the controller outputs a true signal that activates [V5] to supply liquid from the separator[5].

Case-2

The refrigerant leaving the gas cooler/condenser (thermodynamic state 4, identifying the high-pressure HP) is expanded through the high-pressure control valve (thermodynamic state 5). The liquid refrigerant from [5] is partly evaporated through the MT evaporators. The accumulated liquid in the low pressure receiver [6] is supplied towards the LT evaporators as long as there is a certain liquid level inside the low pressure receiver. I.e. once the liquid in the receiver reaches a certain level, the level switch signals the valve [V5] to change the direction and connect the liquid outlet of the low pressure receiver towards the feeding valves of the LT evaporators. The fluid leaving is expanded and passes through the low temperature evaporator (thermodynamics process 8). The vapor from the low pressure receiver[6] is mixed with the fluid flow downstream of the flash gas bypass valve and the part from the LT side before compression (thermodynamic state 3).

Case-2

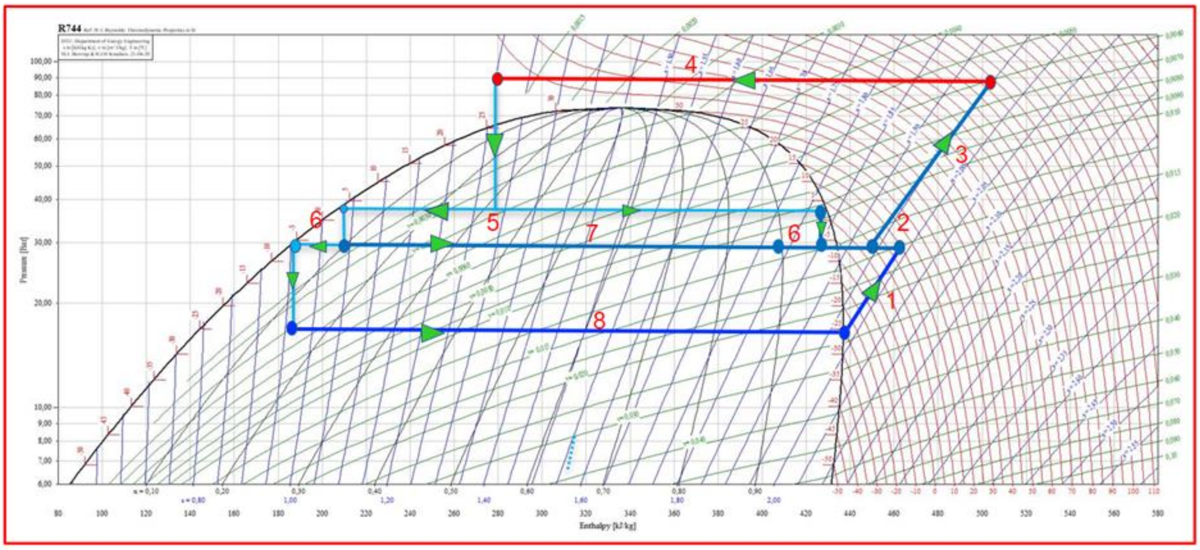


Figure 15 System-8 PH diagram (Case- 2)

❖ **Control approach**

In Case2, the level sensor indicates sufficient liquid level inside receiver [6], when the liquid level is above the setpoint+ hysteresis value, the controller outputs a false Boolean signal to enable to change state of the directional valve [V5], i.e. to activate surplus liquid refrigerant stored at the receiver in order to meet the LT thermal requirements.

In case the liquid level inside the low-pressure receiver reaches the lower level setpoint. Case one mode is activated.

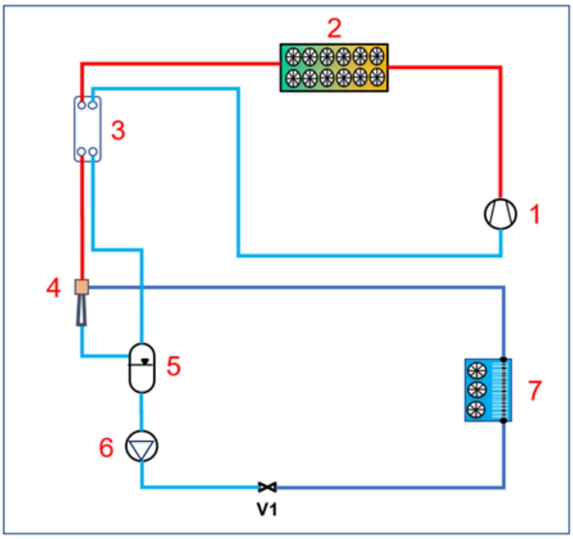
Advantages

Always non superheated operation of the MT evaporators

System-9 “CO_2 only” **Pump supported simple ejector system**

The below system demonstrates the Carrier CO_2 system transcritical system. Hot gas discharged from the compressor(s) [1] flows into the gas cooler [2]. The high-pressure gas is further subcooled through the IHX [3] and subsequently connected to the ejector’s [4] high-pressure port. The ejector actively controls the high side pressure level. While the ejector’s suction pressure port is connected to the saturated vapor leaving the evaporators [7] and the ejector discharge port is connected to the separator [5] where the liquid/gas mixture is separated. A CO_2 pump [6] safeguards the required pressure difference between the liquid receiver and the evaporators, in case of low ejector performance liquid supply to the electronic feeding valve [V1] is maintained. All vapour downstream of the evaporators is passing through the ejector towards the separator. The saturated vapor leaving the upper part of the separator [5] is superheated through IHX [3] before being compressed by compressor [1].

Table 10 System 9 - pump supported ejector system (MT only)

	Components	**Scheme**
1	Compressor(s)	
2	Gas cooler	
3	Internal heat exchanger	
4	Ejector	
5	Liquid separator	
6	Simple CO_2 pump	
7	Evaporator(s)	

V1	Evaporator feeding valve	
		Generalized system

PH diagram and thermodynamics analysis- Figure-16

The refrigerant leaving the gas cooler (thermodynamic state 2, identifying the high-pressure HP) and sub cooled through IHX state 3) is expanded and accelerated through the ejector motive nozzle and mixed with a leaving fluid from the MT evaporator due to pressure difference (thermodynamic process 4). Part of the kinetic energy of the vapor/liquid mixture is converted into a pressure increment via the diffuser where it leaves the ejector at the intermediate pressure (thermodynamic state 5). The vapor/liquid mixture at (thermodynamic state 5) is separated, the saturated vapor is superheated within the IHX and compressed by compressor (thermodynamic process 1). While the liquid fluid is expanded towards the evaporator (thermodynamic process 7)

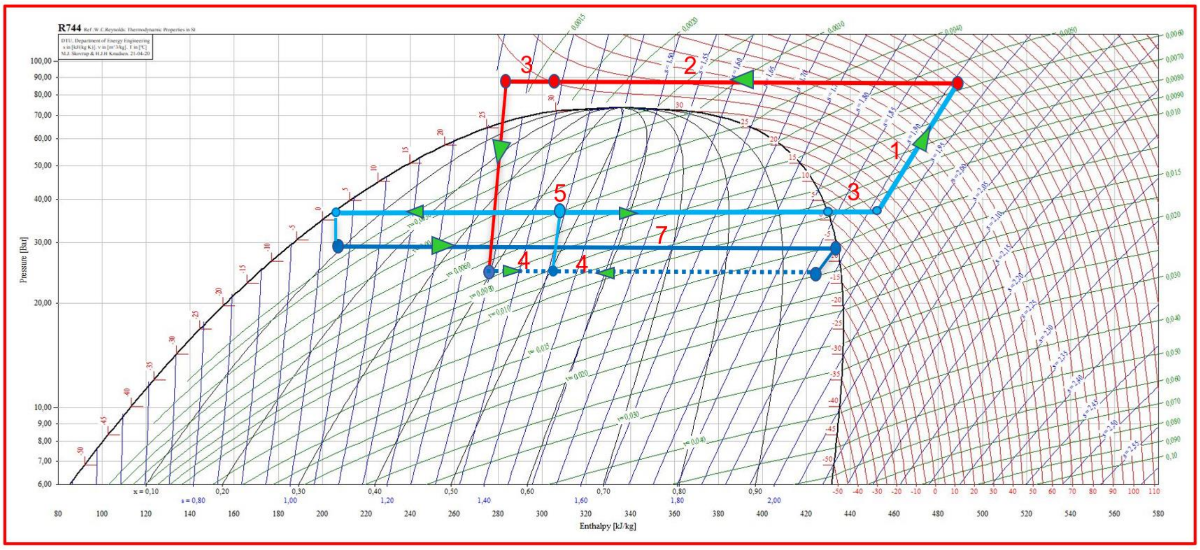


Figure 16 System-9 PH diagram

❖ **Control approach**

The control concept of different components is similar to the previously explained systems.

Depending on available pressure lift of the ejector the CO_2 pump control is compensating in case the pressure difference between the separator and the evaporator is below a setpoint value.

In addition, a logic controller is possible that continuously evaluates the system COP value as a function of evaporator load[7], compressor consumed power[1] and gas cooler rejected heat [2] and compare it to the threshold of the system optimum COP value to output a true/false signal in order to switch ON/OFF the CO_2pump.

Advantages

All time non-superheated operation of the evaporators and utilization of expansion work.

References

Danfoss Multi Ejector and simple system configurations with ejector: https://www.danfoss.com/en/service-and-support/case-stories/dcs/the-danfoss-multi-ejector-range-for-co2-refrigeration/

System 1 **https://cordis.europa.eu/project/id/696076**, see results, deliverable: How to build a new eco-friendly supermarket

System 2 **https://cordis.europa.eu/project/id/696076**, see results, deliverable: How to build a new eco-friendly supermarket

System 3 http://atmo.club/presentations/files/5718e28967fc81461248649xx0Gs.pdf

System 4 https://www.ntnu.edu/multipack, demonstrator Italy

System 5 https://www.ntnu.edu/multipack, demonstrator Portugal

System 6 "Angel Alvarez Pardinas. (2021, September 24). Smart implementation of Multi Ejectors in simplified R744 booster systems for Nordic climates. Norsk Kjøleteknisk Møte 2021, Gardermoen, Norway.https://doi.org/10.13140/RG.2.2.32227.27687 and https://zenodo.org/record/5627860#.YYEwJPnMJaR)"

System 7 https://www.ntnu.edu/multipack, and https://www.ungm.org/UNUser/Documents/DownloadPublicDocument?docId=518600

System 8. Mastrapasqua, F., 2017. EPTA Natural Refrigeration Systems, CO_2 transcritical FTE System. Full Transcritical Efficiency, ATMOsphere Asia/ Bangkok/ (http://archive.atmo.org/media.presentation.php?id=1100)

System 9 Carrier CO_2OLtech https://www.coolingpost.com/products/carrier-opts-for-modulating-vapour-ejectors/ or https://www.carrier.com/commercial-refrigeration/en/eu/media/CO2OLTEC%20EVO%20-%204%20pages_tcm228-12332.pdf

Some of the specific configurations might be protected by the manufactures of these units. The freedom to use these configurations must be explored by supplies intending to implement these concepts in their production portfolio.

However, this e-book intents to highlight and describe the variety of CO_2 refrigeration and heat pump systems and the main control approaches applicable in the context of the MultiPACK project, i.e. units for supermarkets and high performance buildings.

The number of units described will be further extended, an updated version of this e-book will be available online on the MultiPACK website also in the upcoming years.