ENGINEERING TOMORROW

Application Guide

Ejectors in Industrial CO_2 systems Type LP and HP

Improves COP and reduces the swept volume of compressors in CO_2 systems

Contents

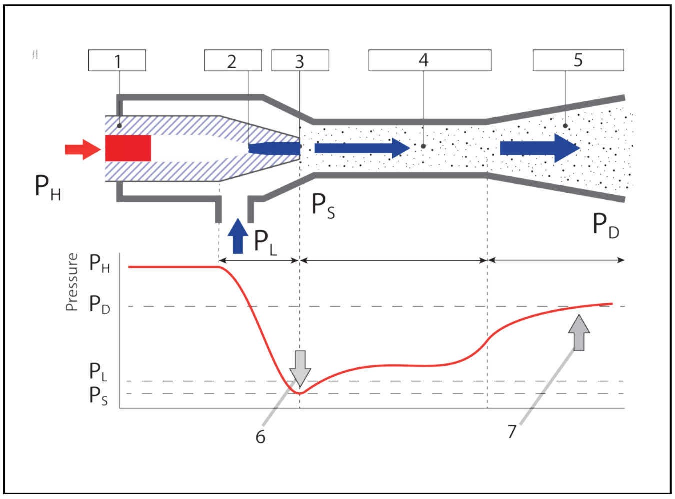
Introduction

Ejectors are in widespread use in the transcritical commercial CO_2 systems and with transcritical CO_2 systems gaining ground in the Industrial sector, Danfoss has developed ejectors of a size that is applicable to these systems.

Ejectors can be used in a number of ways, and this document aims to outline how to do this, including how to control the system with ejectors in and point to the limits of the technology.

The ejector

The ejector is basically a expansion nozzle where the locally very high velocities create a low pressure that can be used to suck additional fluid into the ejector.



1	Motive nozzle
2	Throat
3	Exit
4	Mixing chamber
5	Diffuser
6	Intake due to pressure differential
7	Pressure increase due to reducing flow velocity

- The motive flow port – where high pressure liquid is provided to the ejector to be expanded. At the outlet of the motive nozzle the liquid has expanded and the creation of gas, along with the small dimensions of the nozzle, results in a very high speed. High speed results in low pressure in this area.
- The suction port – connects to the area where the high-speed jet out of the motive nozzle creates low pressure. The pressure at this point becomes lower than the suction pressure and it sucks the flow in the suction port. After this area, the flow encounters a mixing chamber where the expansion is 'finalized' and mixed with the suction flow. The jet expands, resulting in lowering speed which results in higher pressure. Finally, the flow enters the diffuser where the speed drops further, and again the pressure increases.
- The outlet port delivers the combined flow to the receiver at the outlet pressure.

Some ejectors employ a movable needle in the motive nozzle to control the flow in the motive port; however this results in significant losses in efficiency and thus Danfoss has chosen not to do this. This means that the Danfoss ejectors are fixed geometry ejectors. As the ejector functions as a High-Pressure Valve (HPV) in the transcritical system, essentially controlling the gas cooler pressure to the optimal pressure with the given gas cooler outlet temperature, it is necessary to control the capacity of the ejector. With a fixed geometry this is not possible within the ejector itself, but control functionality can be achieved otherwise as described later.

The actual performance, e.g. the flows through the ejector, is a very complex physical problem involving expansion and two-phase flow, which in themselves involve serious deviations when using theoretical calculation. As a consequence, the performance is determined by measurements, and the resulting correlations are implemented in CoolSelector. However, it is beneficial to simplify the ejectors behavior to understand the way it will operate in a system.

It is important to realize that with a given motive port, pressure and temperature the flow through the ejector is basically a fixed value as the geometry is fixed – it can be considered as a fixed Kv value expansion valve. It is not entirely correct though, as the amount of flow through the suction port affects the flow and pressure loss in the mixture chamber and diffuser, and this affects the expansion in the motive nozzle. But once activated the ejector provides the flow that is given by the geometry and, if the flow does not affect the conditions on the 3 ports, this does not change. As in other expansion valves, the motive flow can become supersonic in the motive nozzle which would be the upper limit of possible flow rate, and in that situation the downstream conditions do not affect the motive flow.

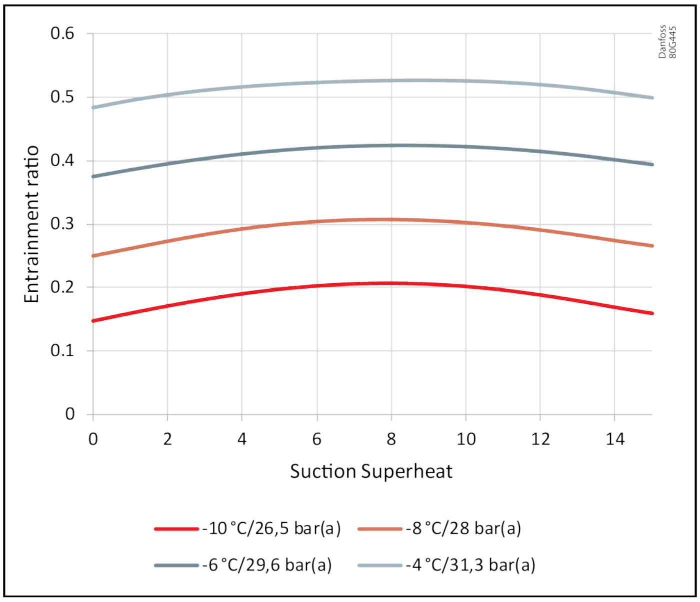
With a given motive and outlet pressure and temperature, the suction nozzle flow depends on the pressure and temperature (affecting the density) on the suction port. A high suction pressure provides a large pressure difference to the low pressure in the jet coming out of the motive nozzle, and this in turn results in a higher flow. Pressure difference is reduced in case there is no superheat. Again, the precise suction flow depends on what happens in the mixing and diffuser (and motive flow is affected by suction flow) but in general a lower suction pressure reduces the suction flow.

Ejectors do not operate efficiently below a too small pressure difference between motive (gas cooler) and outlet pressure, and thus the ejector is stopped via a solenoid valve, and the expansion and High-Pressure control is handled with traditional HPV. As a rule of thumb, the gas cooler pressure, if controlled by the EKE 80 Ejector Controller, is too low when the gas cooler outlet temperature is below approximately 22 °C.

A factor often used to describe the ejector's function is the entrainment ratio, which describe the suction flow compared to the motive flow – expressed in %.

To the right is an example with different MT evaporating temperatures (pressures) and ejector suction superheat between 0 K and 15 K but keeping constant:

- Temperature out of the gas cooler = 35 °C
- Pressure in the gas cooler = 90 bar (a)
- Pressure in the receiver = 38 bar (a)



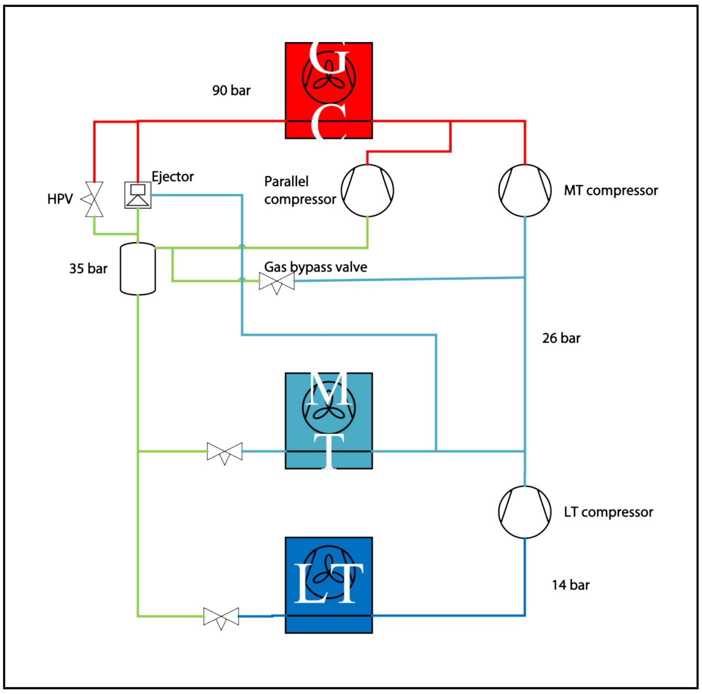
Ejector system types

Ejectors are normally used in several different configurations, which are described below.

High Pressure Ejector

The high-pressure ejector lifts MT flow to IT receiver pressure where it is taken by the parallel compressors. Parallel compressors operate with higher efficiency and require less swept volume than MT compressors, as the suction pressure is higher. This results in savings in both installation and operation.

Figure 2: HP Ejector with sample pressure levels



At lower gas cooler pressures, the ejector and parallel compressors are deactivated, and the gas content of the IT receiver is flashed to MT pressure. This corresponds to traditional booster operation; however, because the gas cooler pressure is low (most likely subcritical), the system efficiency remains high.

As the ambient temperature increases, the amount of gas generated by flashing in the HPV valve increases. In systems without ejectors, it typically becomes beneficial to start the parallel compressors at ambient temperatures of 15 – 20 °C. With ejectors, however, the parallel compressors can be started at ambient temperatures 5 – 7 K lower, allowing the benefits of parallel compression to be utilized over a larger portion of the year.

Using ejectors therefore enhances and extends the effective use of parallel compressors.

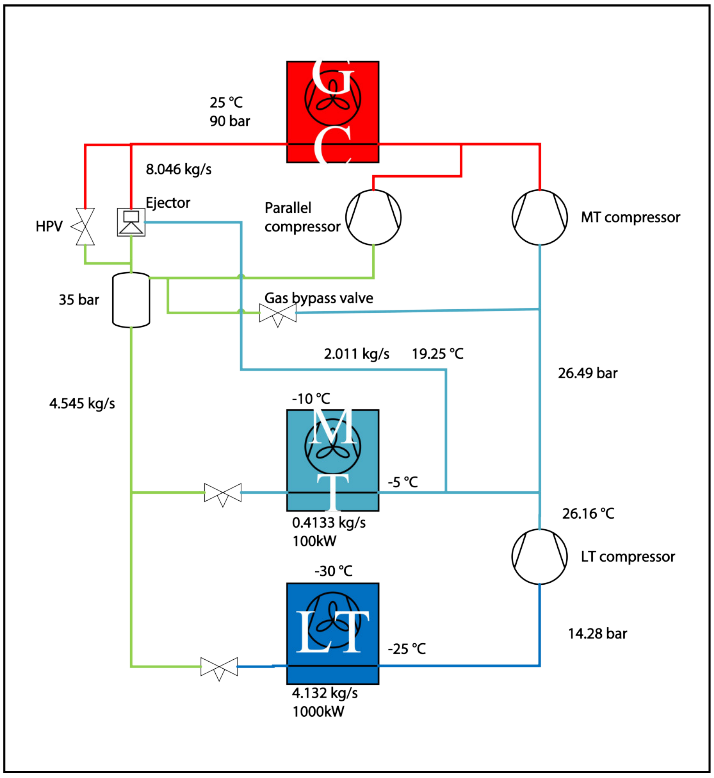
At high gas cooler pressures the ejector is activated, and the suction port takes gas from the MT pressure level (26 bar in the example) and delivers it to the IT receiver at 35 bar, from where it is handled by the parallel compressors. The gas bypass valve is closed.

As mentioned, the ejector started with commercial (supermarket) systems, and these systems pioneered this operational mode. However, the industrial systems often differ somewhat from the commercial systems. One of the differences is that industrial systems often have a large load on the low temperature (LT) circuit while a relatively small on the medium temperature (MT) circuit. If the ejector is sized to accept the entire flow from the gas cooler, then the suction flow can easily accept much more than the MT evaporators can provide. Remember that the ejector does not regulate, it takes the flow its geometry stipulates.

The result is that some of the flow from the LT compressors is taken by the ejector suction port as well. This is not a problem in itself, in fact increasing the system efficiency, but since the LT compressor discharge temperature is very superheated, the resulting mix temperature to the ejector suction port is increased over the temperature from the MT evaporators. The operational envelope of the ejectors stipulate that the maximum superheat in the suction port is 15K. With a very large flow from the LT compressors the gas cooler flow is high, the motive flow is high, and the ejector will have a suction flow that is high as well. If this suction flow surpasses the MT flow to a high enough degree, the suction temperature (superheat) becomes too high, and the ejector is outside its operating limits. The solution is either to desuperheat the LT compressor discharge or to dimension the ejector to take a suction flow that gives a mixture temperature that is within limits. That will result in a motive flow that is smaller than the gas cooler flow so the remaining part will have to be bypassed by the HPV valve or a dedicated balancing valve (see control section).

As an example, the system calculation below shows the problem. The system has an LT capacity of 1000 kW at -30 °C, while only 100 kW at -10 °C. The resultant mass flows in the system yields 8 kg/s out of the gas cooler, which with a realistic entrainment ratio of 25% results in a ejector suction flow of 2 kg/s. Since the MT evaporator only provides 0.4 kg/s at a temperature of -5 °C, the result is that 1.6 kg/s is taken from the LT compressors discharge which is at 26 °C. The mix temperature of these flows is 19 °C which is outside the ejector's envelope.

Figure 3: Example of ejector suction temperature problem



If the ejector suction flow is limited to 1.2 kg/s, then 0.8 kg/s is taken from the LT compressor discharge, and the resultant mix temperature is 15 °C which is (just) within the ejector envelope. With an ejector entrainment ratio of 25% that means that the ejector motive flow should be 4.8 kg/s, e.g the remaining gas cooler flow should be handled by the HPV. This is a reduction of the ejectors effect on the system but since ejector operation is not allowed with the above operating conditions, this is better than nothing.

Low Pressure Ejector

The low-pressure ejector takes the entire flow from the MT evaporator and lifts it to the IT tank pressure. In this way, the MT compressor suction is no longer directly tied to the MT evaporating pressure and can operate at a higher pressure, resulting in improved compressor efficiency.

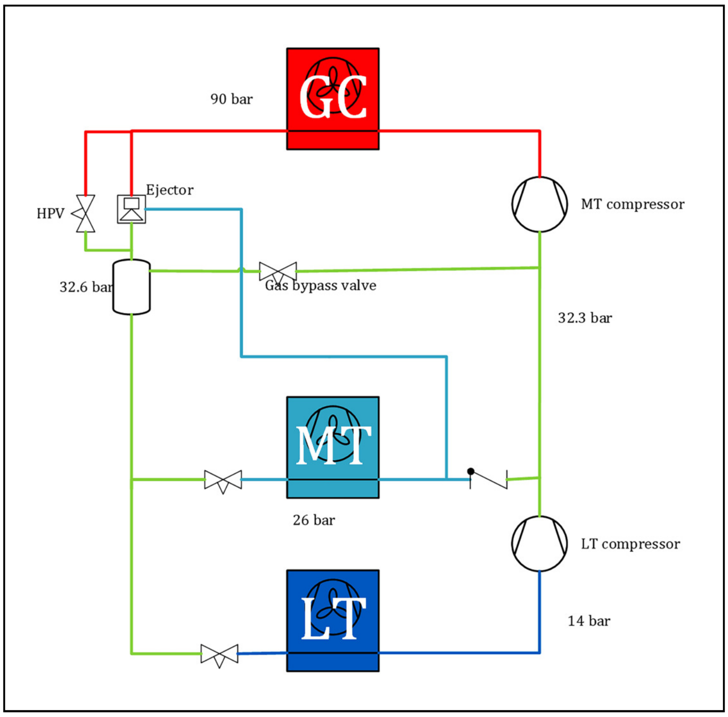
The MT compressor suction pressure can be set slightly below the IT tank pressure—sufficient to allow adequate flow through the gas bypass valve. As the LT compressor discharge pressure increases, the efficiency of the LT compressors decreases, partially offsetting the efficiency gains achieved in the MT compressors. If the LT load is relatively high compared to the MT load, the overall efficiency gain may not be positive. In such cases, an HP ejector system is recommended. This assessment must be made during the system design phase.

When the ejector is activated, the check valve in the MT evaporator line to the LT discharge/MT suction line closes as the MT evaporating pressure drops, allowing the LT discharge/MT suction pressure to remain above the MT evaporator pressure.

When the ejector is not activated, such as during low gas cooler outlet temperatures (low gas cooler pressure)—there is no flow in the

ejector suction line, and the MT compressors must handle the entire flow. In this operating mode, the MT compressor suction pressure and MT evaporator pressure are the same (minus the check valve pressure drop), and the system operates as a conventional booster unit. As this occurs at low gas cooler pressure (most likely subcritical), system efficiency remains high.

Figure 4: LP ejector with sample pressure levels



When the ejector is activated (high gas cooler outlet temperature) the ejector controls the evaporating pressure. As mentioned, the ejector itself cannot regulate, so the HPV valve or a dedicated balancing valve (see control section) needs to regulate the flow to the ejector motive port that results in an ejector suction port flow that keeps the MT evaporating pressure at the right level.

Ejector control

The ejector replaces the HPV in the transcritical system and controls the gas cooler pressure. However, as mentioned earlier, the fixed-geometry Danfoss ejector cannot regulate capacity due to efficiency considerations. The solution is to use multiple ejectors and, if required, a (small) HPV valve to smooth the steps between ejector capacities. In this context, the small HPV is referred to as a balancing valve.

Consequently, the ejector shown in the above application drawings consists of an array of ejectors combined with a balancing valve.

In the commercial sector, this regulation challenge was addressed through the development of the Danfoss Multi Ejector. This unit consists of a housing capable of accommodating up to seven ejector inserts of different sizes. The variety of insert sizes allows different combinations to be activated, providing effective capacity regulation by selecting which ejectors are in operation.

Figure 6: The Danfoss Multi Ejector

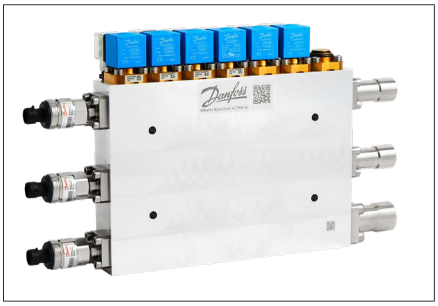
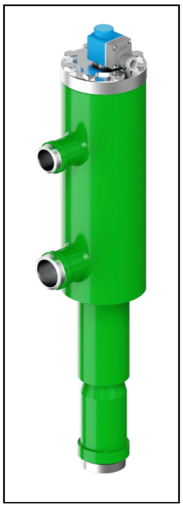


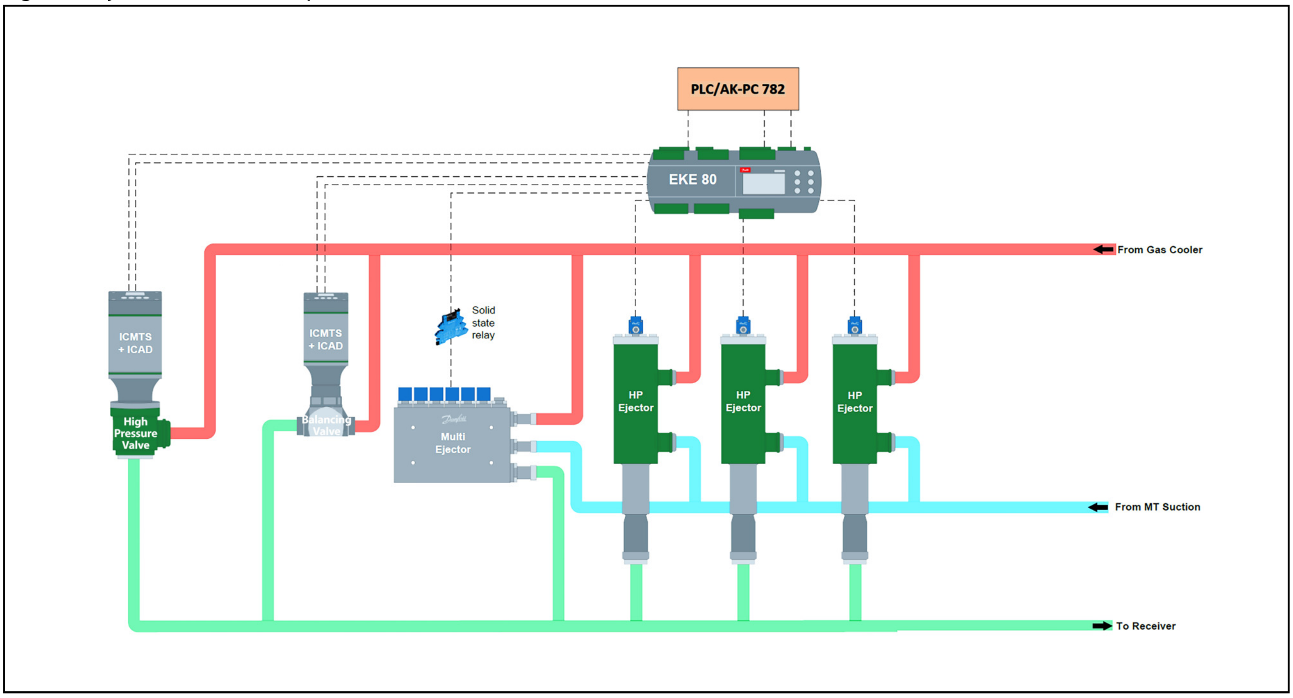
Figure 7: The Large CO_2 Ejector



The Danfoss Multi Ejector is relatively small and thus usually not enough for industrial applications. This prompted the development of the Danfoss Industrial Ejector. This ejector comes in 3 different sizes with much higher capacity than the Multi Ejector.

Additionally, the ejectors should be paired with the EKE 80 Ejector Controller allowing for a smooth regulation across the entire capacity range, by sequencing the ejectors sensibly.

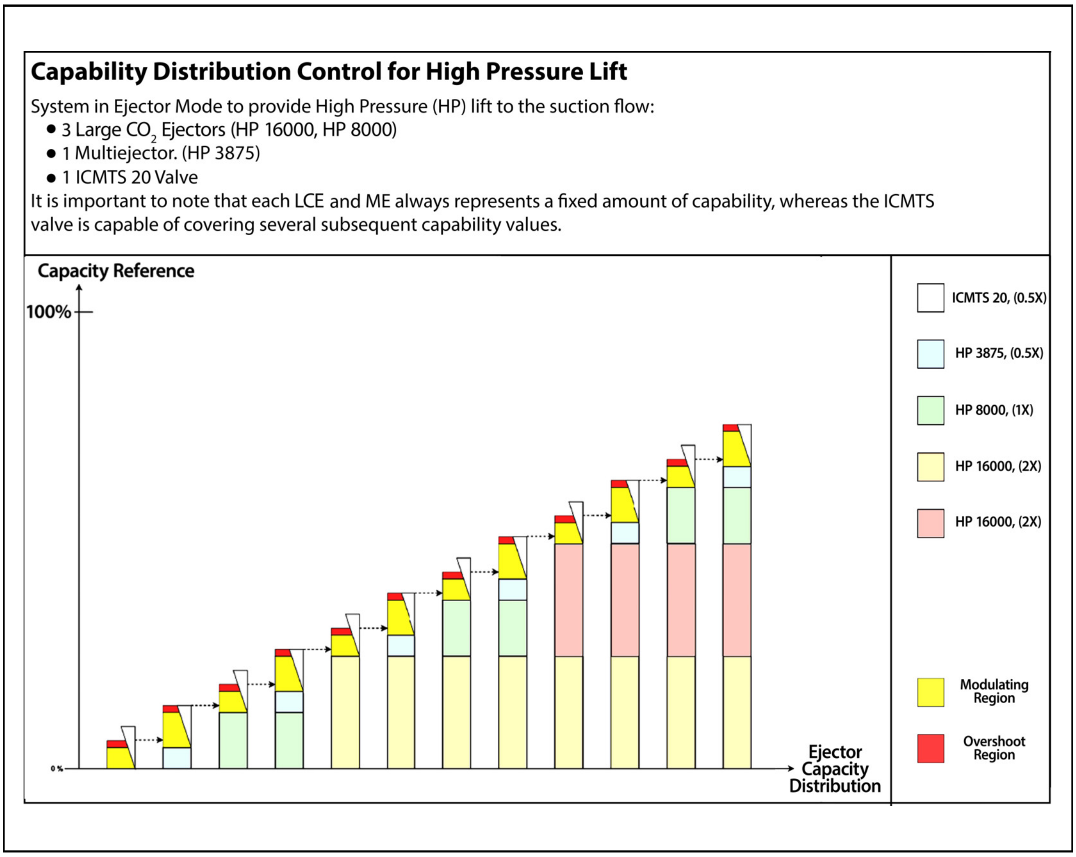
Figure 8: Ejector control example 1



The above configuration sequences the three industrial ejectors (right) and smooths the capacity steps between them using the multi-ejector (center). For even finer control, a balancing valve (right valve) is applied.
If the gas cooler pressure becomes too low for efficient ejector operation, the HPV (left valve) takes over and controls the system as it would without ejectors. The EKE-80 also controls the HPV.

The sequence of ejector activation could look like the chart below.

Figure 9: Capacity distribution for HP Lift in an example system consisting of 4 LCE, 1 ME and 1 ICMTS 20 balancing valve with an increasing capacity reference value



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