Booster Vapor-Compression Refrigerating Systems

Dmytro Buyadgie
Wilson Ltd

Vitaliy Sechenyh
Wilson Ltd

Sergii Nichenko
Wilson Ltd

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Dmytro BUYADGIE[1], Vitaliy SECHENYH[*1,2], Sergii NICHENKO[1,2]

[1]Wilson Ltd,
Odessa, Ukraine
tel.: +380 48 7343010, fax: +380 48 7342010,
e-mail: office@wilson-ukraine.com
[2]Odessa State Academy of Refrigeration,
Odessa, Ukraine
tel.: +380 48 7232220, fax: +380 48 7231145
e-mail: admin@osar.odessa.ua

ABSTRACT

Present study describes simple and reliable methods of refrigerating systems functioning at compressor's pressure ratio above 7-10. Its concept lies in preliminary throttling of condensed working fluid to intermediate pressure level. Segregated vapor ejects low-pressure vapors before suction into compressor. In this case, less ballast vapor is supplied to evaporator. Remaining vapor expands in the ejector's nozzle and perform preliminary compression of low-pressure vapor before compressor. It results in compressor's volumetric efficiency increase by 25% with simultaneous decrease of consumed power by 20% subject to ratio of condensation and evaporation pressures. COP of the system can be increased by 25-45% and system may have several expansion stages depending on different temperature levels. It leads to peak usage of ballast vapor's exergy.
The device consists of liquid separators and expansion stages. Throttling valves or two-phase jet expanders could play a role of the expansion stages. In comparison with original two-phase ejector scheme, proposed system has an important advantage - major part of ballast vapor, formed in the nozzle of two-phase ejector, has to be compressed from the lowest pressure in the cycle.
Calculations have shown that COP of the proposed system is 10-15% higher comparing to scheme with two-phase ejector.

1. INTRODUCTION

Refrigeration Services has become widespread throughout the world and belongs to one of the most power-consuming industries. Each element of modern refrigeration unit, during many years of researches, brought to near perfection, that is energy and operational characteristics of vapor compression refrigeration machines have almost reached their limit.
Nevertheless, it appears that there is still room to improve energy efficiency of this type of machines, and it lies within the cycles. There are two options for improving the COP of single-stage cycle with high ratio of the condensation pressure to the pressure of evaporation. This is, firstly, the utilization a part of compressed in the compressor vapor in ejector booster stage to increase the suction pressure, that leads to an increase in volumetric characteristics of the compressor and reducing power consumption. Secondly, a replacement of throttling of liquid refrigerant after the condenser with process of liquid expansion in the nozzle of the ejector and utilization of the expansion work of the liquid to increase pressure after evaporator. Both of these methods will increase the COP of the refrigeration system by the 2-10% that does not always justify the application of these methods. The paper provides an analysis of the new system booster compression, which uses exergy of ballast vapor after preliminary throttling, which improves the COP by 25-35%.

2. BOOSTER REFRIGERATING SYSTEMS

Cooling systems are designed to work within a wide range of operating parameters, that is related both with required cold of variable temperature and with the variable ambient temperature. Designing of the system functioning in extreme conditions, i.e. with the lowest evaporation temperature and the highest condensation temperature is irrational, because these conditions usually are occurred sporadically. If not take into account such cases means non-compliance of given technology. Therefore, other ways to ensure the smooth operation of the system should be

considered. These include:
-Transition to two-step compression by switching the compressor cylinders;
-Accumulation of cold;
-Device of booster jet stages.
The first two methods are related to a more complicated schemes with a substantial increase in weight and dimensions of the refrigeration system. The third method is extremely simple, efficient and tiny.
Scheme of (Badylkes and Danilov, 1961) is long been known, which is designed for short-term use in the scheme of single-stage vapor compression machines for the compression of low pressure vapor in cases when there is the necessity to significantly reduce the evaporation temperature or when the condensation temperature has a peak value. In general, such systems can be used in refrigerated trucks that carry a variety of goods that requires different temperatures in the chamber, and, if necessary, can be used for rapid freezing of cargo when it is not possible to implement it in advance. This scheme becomes effective, from T_o <230K, and at higher temperatures its COP is less than without the ejector.
Compared to the booster scheme of (Badylkes and Danilov, 1961), when for ejector functioning a compressed in the compressor vapor, which is intended to produce cold, is used, the proposed scheme has a fundamental difference related with a decrease in power consumption (Fig. 1). Its essence is that after the condensation the preliminary expansion of the liquid is performed, after which the separated intermediate pressure vapor presses vapor before the suction into the compressor. In this case the less ballast vapor is fed to the evaporator, but the vapor that is fed to the ejector nozzle ceases to be the ballast, as it performs work on preliminary compressed low-pressure vapor to the compressor. The consequence of these arrangements is the increase of the volume characteristics of the compressor by 25% and decrease of power consumption by 20%, depending on the pressure ratio of condensation and evaporation. Thus, the COP of the system can be increased by 25-45%. Compared with the two-phase ejector expander (TPEE) (Fig. 2), this scheme also has the great advantage due to the fact that most of the ballast vapor, with is generated by the expansion of the liquid in the nozzle of the TPEE, must be compressed from a lowest pressure in the cycle. It should be noted that the specific work of expansion of the liquid is one order lower than that in the expansion of vapor. However, the application of TPEE at low evaporation temperatures lead to a noticeable, by 15 -30%, increase in specific cooling capacity of the cycles, which indicates the possibility to optimize the cycle with both jet devices in one scheme. Results of separate calculation for each of the schemes have shown that the COP of the proposed scheme by 10-15% higher than the scheme with the TPEE.

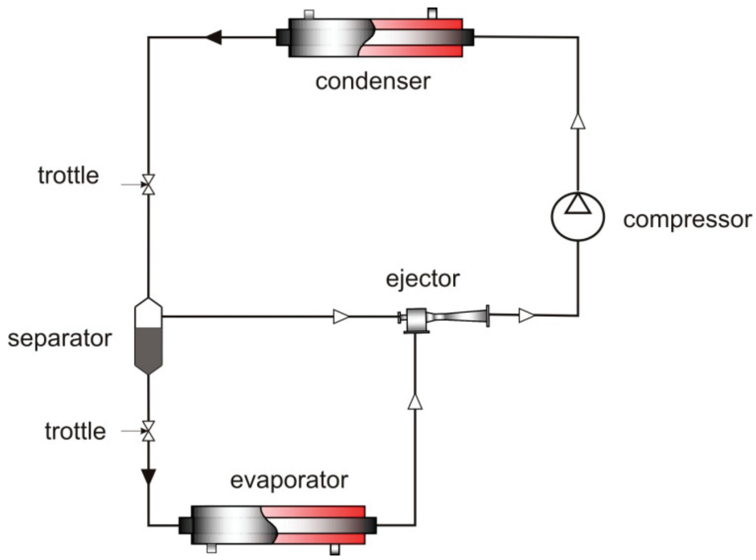

Fig.1 Ejector booster system.

Scheme of two-temperature setup is also known, which uses an ejector as a pressing stage, but it is not effective enough for the following reasons: as a working fluid in an ejector all the vapor is used, that is coming from the high-temperature evaporator, which has very low operating pressure, i.e. low exergy, to be able to any appreciable increase of the pressure of the total flow from the lowest pressure in the cycle. This means that the compressor will need to perform the compression of the entire flow from the pressure, almost equal to the pressure of evaporation in

the evaporator, to condensation pressure. According to the authors calculations the COP is increased by 9,5%, and the main part, apparently, falls to the increase of the specific cooling capacity due to supercooling of the condensate vapor after the ejector. However, as is well known, that ammonia machines operate with a minimal overheating, so this heat exchange may adversely affect the efficiency of the compressor due to the high temperature of the compression end.
Thus, the best is to use the proposed scheme with stepwise throttling and pressing of the vapor with ejector.

3. OPTIMIZATION OF CYCLE INTERMEDIATE PARAMETERS AND WORKING FLUIDS

Cycle with booster ejector, which uses a ballast vapor after the first throttling, has the COP, which depends on many parameters, and each of them has a different effect on the result. Entrainment ratio is determined by the vapor quality after the first throttling and is a known parameter of the cycle. The maximum attainable pressure after the ejector depends on both the intermediate pressure and the entrainment ratio. Thus, all parameters are related to each other: the higher the vapor quality, the lower the entrainment ratio and the higher the achievable pressure in the ejector outlet on one hand. Increasing of this pressure means that the volumetric efficiency of the compressor is increasing, and thus the cooling capacity of the compressor, and effective power of the compressor is decreasing. However, on the other hand, the working pressure is lowering that in the opposite direction affects the achievable pressure in the ejector and the volumetric compressor characteristics. This indicates the presence of an extremum of the pressure, which is reflected on the plot of the volumetric efficiency with the intermediate pressure (Fig. 2). The absolute value of the maximum attainable pressure depends also on the ratio of the parameters of the cycle and the critical parameters of refrigerant. The closer the parameters of condensation to the critical point, the greater the increment of the COP can be obtained in the cycle. As it can be seen from the graph, the highest values of the volumetric efficiency are obtained for the R-125, and the lowest are for ammonia. A similar pattern can be seen for the COP (Fig. 3), only the peaks are more pronounced, because the COP also is influenced by the specific cooling capacity, which increases with the application of intermediate throttling.

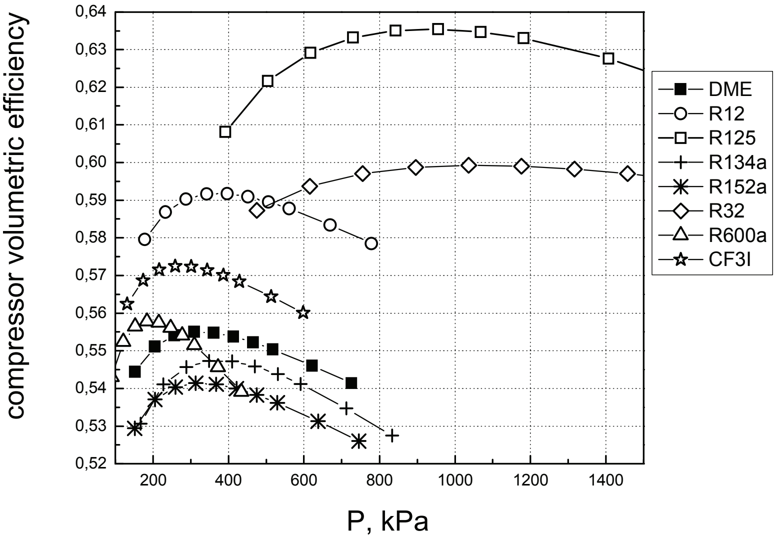

Fig. 2 Volumetric efficiency of the compressor vs. pressure of the intermediate stage

If you look for different regimes the maximum growth of volumetric efficiency of compressor depending on the temperature of condensation and evaporation (the boundaries of cycle) for two refrigerants, R-125 and R-132, which has maximum effect from the application of this scheme, it is easy to see that the more difference between the temperature of evaporation and condensation, the more significant increase of entrainment ration is observed (Fig. 4). The final effect – COP – behaves the same way, only the gap between the COP without and with ejector is higher (Fig.5). In cycles with a high evaporation temperature increment of COP is around 10-15%.

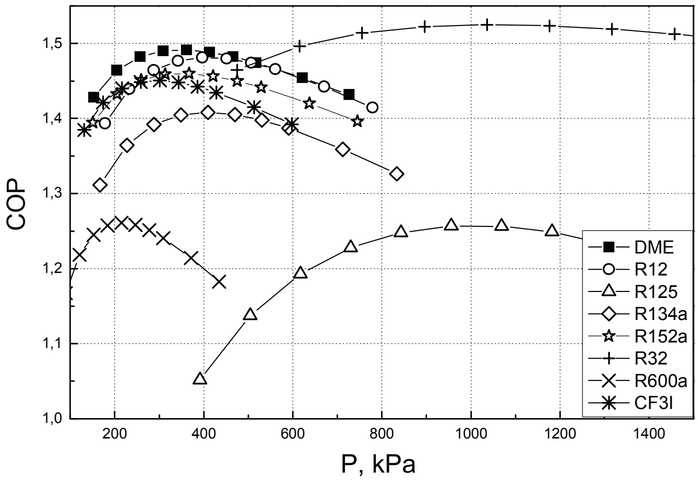

Fig. 3 COP vs. pressure of the intermediate stage

4. REPLACING OF THE THROTTLE DEVICE ON TWO-PHASE JET EXPANDERS

Recent years a number of studies of two-phase ejector (Raghuram, 2009, Kim and Lee, 2007), which use a liquid of high pressure as primary flow, and gas or vapor serves as secondary flow. The literature describes a method of calculation of water-air ejector (Sokolov an Zinger, 1989), however, for the refrigerating system, this technique has undergone refinements and modifications, taking into account the thermophysical properties, as well as state of the liquid before the nozzle that is close to saturation, that leads to its boiling in the flow part of the ejector. Unfortunately, CFD-simulation of jet devices has not yet managed to implement. Nevertheless, calculations within the usual method, considering the changes, allow with a high degree of accuracy to determine the basic parameters of the device. Figure (6) shows a schematic diagram of a vapor compression refrigeration unit with TPEE, which allows to make the process of expansion more reversible and thus get an increment in the cooling capacity in the cycle.

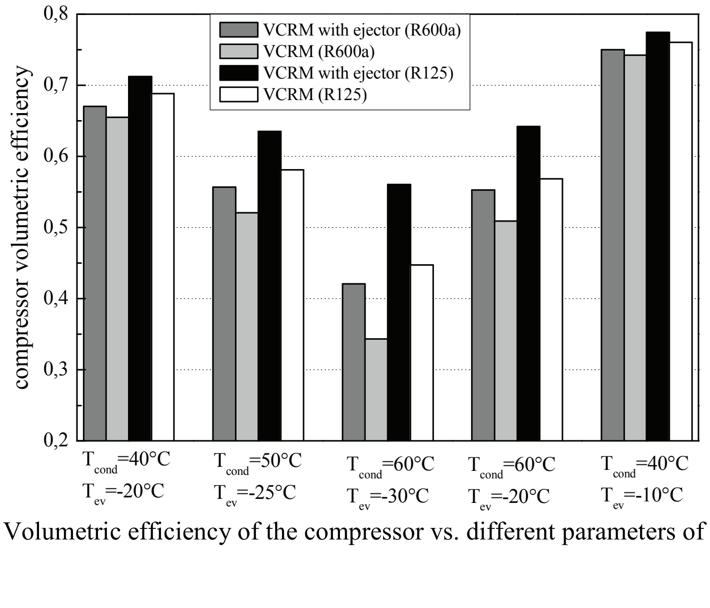

Fig. 4 Volumetric efficiency of the compressor vs. different parameters of cycle

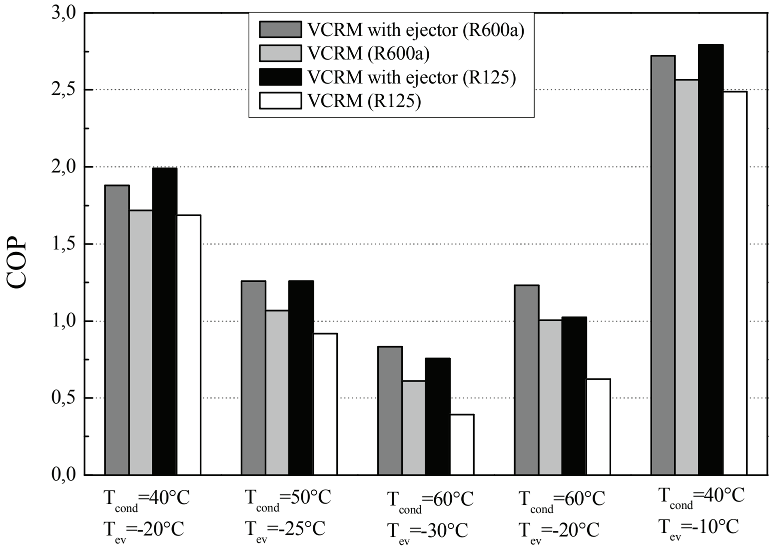

Fig. 5 COP vs. different parameters of cycle

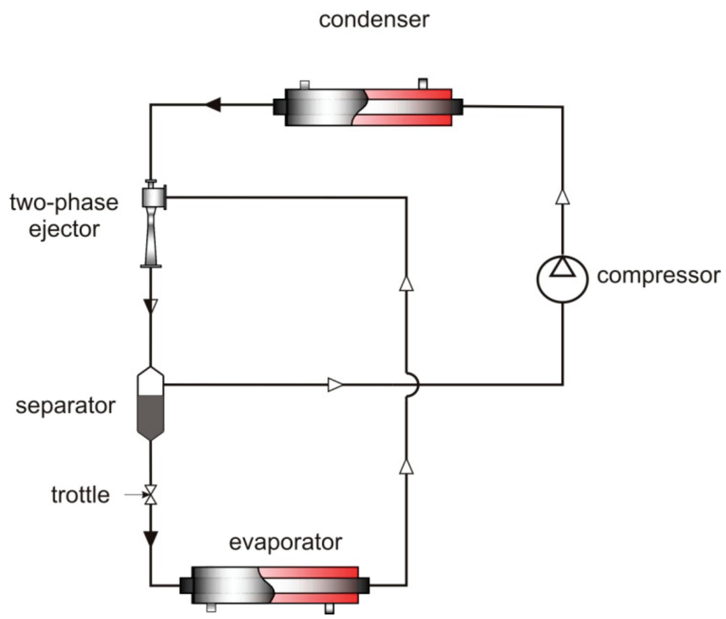

Fig. 6 Scheme with ejector as expander

Comparative calculations of volumetric and energy characteristics of the refrigeration machine with throttling and expansion in TPEE showed that in different regimes for refrigerating machines operating on R-600, there is a considerable increase in cooling capacity (by 20%). But the growth of volumetric efficiency and drop of the power consumption ranges the margins of calculations error. Thus, the growth of system COP is due, almost entirely, to the growth of the specific cooling capacity. The calculation results are shown on the graph (Fig. 7). For comparison, in the same format a graph of the refrigeration system performance with booster ejector is constructed. (Fig. 8). In this case, the growth of COP reaches 35%, while decreasing of power consumption of the compressor is almost 20%.

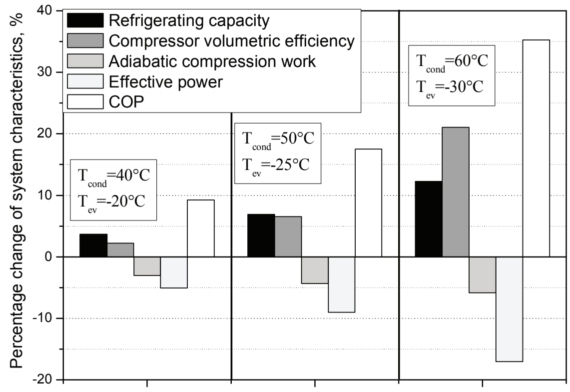

Fig. 7 Effect of booster system application (for isobutane)

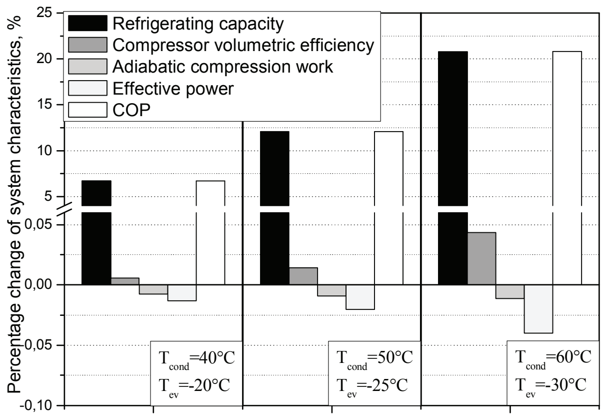

Fig. 8 Effect of ejector application as an expander (for isobutane)

5. CONCLUSIONS

As it shown in the report, the use of booster ejector devices, which are compact and simple devices, consisting of an ejector and a liquid trap, leads to an increase of COP from 10% in the mode of air conditioning to 35% at the boundary cycle temperatures, which are the condensation temperature 60°C and evaporation temperature -30°C, for isobutane. Decrease in compressor power reaches 20%. The growth of the COP, caused by the use of TPEE, is almost twice lower. Application of these arrangements can lead to high energy savings for the production of cold, and, consequently, to reduce CO2 emissions into the atmosphere.

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