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Expanders in refrigeration system - general information

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Abstract

The paper presents the causes of research on the use of expanders in refrigeration systems. The possible types of expander are introduced. The turbine expander was selected for the comparative analysis. The results of theoretical and experimental work on cooling cycles with carbon dioxide as refrigerant in the supercritical and subcritical systems equipped with turbine decompressors were presented. It has been proven that the use of expanders has enabled energy savings in the level of 25%.

Keywords: refrigeration, expander, expander efficiency.

1 Introduction

There are several ways to increase the energy efficiency of a refrigeration unit. Each component of the circuit has specific energy losses. Particularly throttling is a process during which the medium irreversibly loses its ability to do work, even though its enthalpy remains constant.

2 Refrigerant's throttling losses

Two types of losses occur during the throttling process:

- loss of specific cooling capacity caused by increase of the refrigerant's dryness
- work loss due to unused pressure difference

Throttling losses are determined by the values of temperature, operating pressure and refrigerant properties. For circuits with carbon dioxide, these losses are especially noticeable because of the high pressure difference occurring in the gas cooler and evaporator, which can be as high as 100 bar.

The throttling loss can be decreased with:

- subcooling of the liquid before throttling
- use of multi-stage or cascade circuits
- use of components or devices in which throttling-free expansion occurs.

So far, the first two methods have been used successfully. The third method is now becoming more important due to the possibility of generation of mechanical work. In perspective, this increases the energy efficiency of the refrigeration system.

3 History

The history of theoretical considerations and experimental research on expansion devices in refrigeration circuits is long and dates back to the late 1980s. Then, the Norwegian scientist Gustav Lorentzen (born January 13, 1915, died August 7, 1995) in his research on refrigeration circuits returned to carbon dioxide as a refrigerant known from the 19th century [3]. He developed a method for the regulation of stable operation of equipment. Between 1988 and 1991,

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he proposed a transcritical circuit model. In his paper in 1993, he was the first who proposed the use of a throttleless expansion element in a carbon dioxide system to improve energy efficiency [4].

The use of a throttleless expansion device instead of an expansion valve increases the unit cooling capacity and also enables the generation of mechanical work.

This device is an expander, which throttles the working medium in a way close to isentropic expansion [3, 4, 7] i.e., a conversion intermediate between isentropic and isentropic expansion.

Robinson and Groll, 1998, presented a theoretical discussion that included a comparison of throttle valve and expansion turbine circuits [7]. In their paper, they focused on the calculation of the cycle efficiency and the selection of the optimum gas cooling pressure. They did not address important issues related to the technical design of such an expander.

4 Expanders

Zhang Bo stated that any compressor can be used as an expander, it only needs to be reversed [8]. Thus, the possible candidates to work as expanders in CO2 circuits are:

- turbine,
- crankless reciprocating compressor,
- scroll compressor,
- screw compressor,
- rotary vane compressor,
- rotary piston (rolling pison) compressor.

Hiwata proposed another way of dividing expanders [1]. The criterion for the division is how the mechanical work is output from the expander:

- There is a compressor, an expander and an electric engine on a one shaft. The expander drives an electric generator, which can be used to power the compressor.
- Two-stage compression is used: main compressor as the first stage, compressor-expander system as the second stage.
- Two-stage compression is used: compressor-expander system as the first stage, main compressor as the second stage.

5 Turboexpander

In 2014, Hou and his team presented their work on microturboexpander for carbon dioxide expansion in the transcritical cycle [2]. The work was theoretical and experimental in nature. The authors theoretically analyzed a circuit with an expansion valve and with a microturboexpander. Then they designed and fabricated a transcritical circuit for carbon dioxide.

The design cooling capacity of the circuit was 15 kW. The system included two microturboexpanders for the refrigeration circuit with a 10.6 mm radius turbine and a 10.1 mm radius impeller, rotating at speeds up to 180,000 rpm. The expanders were designed to operate in both two-phase flow and one liquid phase flow of carbon dioxide. The main obstacles to the use of turbines in refrigeration circuits are the required high shaft speed and the lack of theoretical (and practical) studies of turbines with two-phase flow with a high proportion of liquid phase. In recent years, however, there have been significant advances in materials engineering and design tools. In particular, gas bearings and magnetic bearings should be mentioned. All these discoveries have together contributed to the applicability of turbines in refrigeration systems.

The operation of two turboexpanders was analyzed:

- the first one realized full expansion, at the outlet there was two-phase flow
- the second one realized half-expansion, at the outlet there was liquid flow

In the case of expansion valve operation, the efficiency ratio of the system was 2.31. However, when full expansion was realized, the efficiency ratio increased to values in the range of 3.01 to 3.04 depending on the assumed isentropic efficiency of the expander. This provided an increase in efficiency from 24.9 to 26.3%. In contrast, when a half expansion was implemented, a coefficient of performance of 2.48 to 2.52 was recorded, which translated into an increase of 7.3 to 9.3% (assuming the same isentropic expander efficiency).

Turboexpanders in refrigeration technology have previously been used in equipment for condensing gases below 120K. They have many advantages: high efficiency, small size, easy operation, tightness and high reliability. Therefore, according to the authors, they are the best alternative to the expansion valve.

6 Expander in a refrigeration systemn - an example

A carbon dioxide system with an expander created teretically in 2003 by Nickel and Quack [6] will be used for the description. In 2006, the authors presented data on a circuit with an expander operating under actual conditions [5]. A cooling system is installed in a COOP supermarket in Wettingen, Switzerland. During summer the air temperature is higher than the critical point temperature of carbon dioxide. This means that the refrigeration system operates in transcritical circuit mode. The expander in question was designed precisely for these operating conditions.

In the European climate, the ambient temperature is much lower than the critical point temperature most of the time during the year. Thus, the pressure in the condenser drops below 70 bar. As a result, the system has to operate in subcritical mode. However, summer conditions require the unit to be able to operate in supercritical mode as well.

Previously, carbon dioxide systems had already been implemented in supermarkets. However, they worked only in the low- and medium-temperature parts of the system, due to the unfavorable operating conditions at high ambient temperatures.

Nickl and Quack, who designed the sysytem, had expected the unit to consume more energy than a comparable unit running with R404A refrigerant. However, it turned out that the consumption remained at a similar or even lower level. The researchers gave reasons for this situation:

- The effective evaporating temperature for carbon dioxide is 3 K higher than for R404A. This is because carbon dioxide has better heat transfer coefficients than R404A and lower relative suction pressure losses.
- In winter, systems with R404A must maintain high condensing pressures for the expansion valve to operate properly. In systems with R744, condensing pressures can be reduced due to the fact that the pressure at the various points of system operation allows the expansion valve to operate in a stable way.
- Higher ambient temperatures where carbon dioxide has lower efficiencies than R404A do not occur under the given climatic conditions (Switzerland).

Above mentioned refrigeration system was designed to operate at a gas cooler pressure of 115 bar. To build such a system, the following were needed:

- compressor with a suction pressure of 30 bar and a discharge pressure of up to 115 bar
- a special heat exchanger on the high-pressure side to allow gas cooling under transcritical conditions and vapour condensation under subcritical conditions.

With the use of an expander in place of an expansion valve, high efficiency gains were expected. A group of scientists, headed by Nickel and Quack, worked for many years to develop such an expander that could be used in an actual refrigeration system. The third generation of proposed devices met such expectations.

The cooling system in the supermarket in Wettingen consists of two circuits: a low and a medium temperature circuit, both running with carbon dioxide. It was decided to convert the medium temperature circuit to run with an expander. A scheme of the system before and after modification is presented below [Fig. 1].

One component of the system is a separator/liquid reservoir. It operates at a pressure of 10 bar above the evaporating pressure. The steam that is generated at the first expansion valve (5-6) is led directly to the suction part of the system. The liquid from the separator is divided into several small streams, which are throttled directly before the evaporators. As already mentioned, the expander should replace the expansion valve in this system. The original system has three expansion valves (5-6, 8-9, 7-10). The first two stages of the expander will replace valve 5-6, while the third stage will replace valve 7-10. Valve 8-9, located directly upstream of the evaporators for technical reasons, must remain in the system. The compressor fed by the expander works as a second stage compressor.

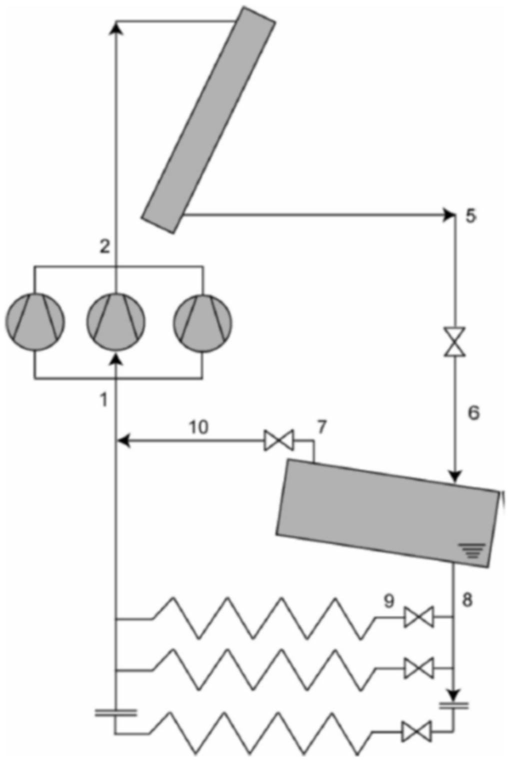

Figure 1. Overview of refrigeration circuit diagrams (by Nickl and Quack)

The integrated expander/compressor unit is located near the liquid separator. The disadvantage of this solution is the need to run two additional pipes to the gas cooler, which is located on the roof of the building. The modification of the system was to provide higher efficiency of the system in two operation modes: subcritical and transcritical without the expander. This can be achieved in the subcritical mode of operation by using parallel operation of an electrically powered main compressor and an auxiliary compressor driven by an expander. Three-way valves and an control unit allow the system to be switched from staged to parallel operation and reverse. Depending on the temperature, subcritical or transcritical mode of operation is activated.

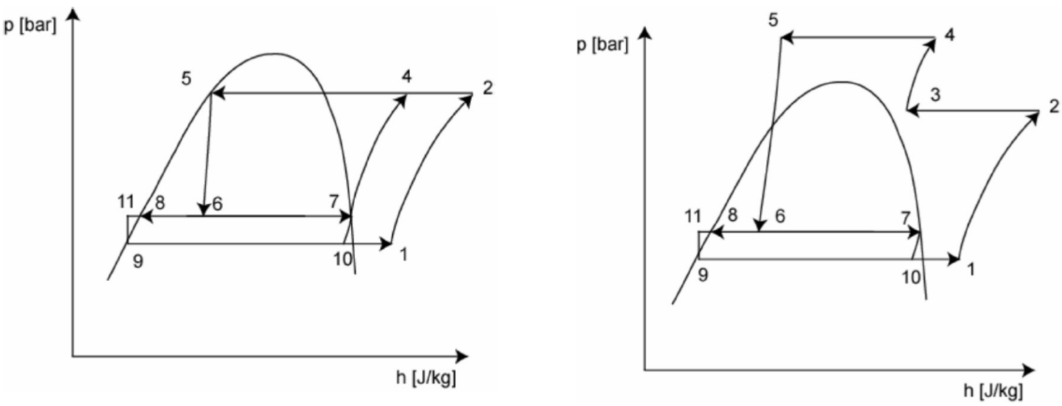

Figure 2. Circuit diagrams on pressure-enthalpy graphs (by Nickl'a iQuack'a)

Thus, the authors compared theoretically and experimentally three systems: a circuit with R404A refrigerant, a circuit with R744 with an expansion valve, and a R744 circuit with an expander. The use of R404A results in lower energy consumption compared to R744 without an expander when outdoor temperatures exceed 27^{o}C. In contrast, R744 without expander performs better at temperatures below 13^{o}C. Over the entire range of cooling capacities, a system using R744 with an expander, which works in supercritical or subcritical mode depending on the weather conditions, provides energy savings of up to 25%.

7 Conclusions

The expected manufacturing cost of the expander will not exceed 1/3 of the cost of the system's main compressor. Both the initial estimates and the tests carried out on the actual circuit confirm the fact that the circuits with the expander are ideally suited for use in supermarket refrigeration systems. The expander can be integrated into an existing system which effectively reduces the overall system costs. In order to guarantee safe operation over a larger pressure range several additional valves have to be fitted to the system.

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