Applied Thermal Engineering 99 (2016) 866–872

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Comparative analysis of energy improvements in single transcritical cycle in refrigeration mode

V. Pérez-García [a,*], J.L. Rodríguez-Muñoz [a], J.J. Ramírez-Minguela [b], J.M. Belman-Flores [c], S. Méndez-Díaz [d]

[a] Department of Metal-Mechanical, Universidad Tecnológica del Suroeste de Guanajuato, UTSOE, Valle-Huanímaro km 1.2, Valle de Santiago, Guanajuato, C.P. 38400, Mexico
[b] Department of Chemical Engineering, Universidad de Guanajuato, DCNE, Col. Noria Alta s/n, Guanajuato, Guanajuato C.P. 36050, Mexico
[c] Department of Mechanical Engineering, DICIS, Universidad de Guanajuato, Salamanca-Valle de Santiago km 3.5 + 1.8, Salamanca, Guanajuato C.P. 36885, Mexico
[d] Faculty of Mechanical and Electrical Engineering, Universidad Autónoma de Nuevo León, San Pedro de los Garza, Nuevo León C.P. 66451, Mexico

HIGHLIGHTS

- A performance analysis of three configurations in transcritical cycle is realized.
- Recommended conditions for use of ejector in transcritical cycle are presented.
- A cooling capacity comparison among three configurations is presented.

ARTICLE INFO

Article history:
Received 27 October 2015
Accepted 20 January 2016
Available online

Keywords:
Transcritical cycle
Ejector
Internal heat exchanger
Turbine
Carbon dioxide
COP

ABSTRACT

One solution to increase the energy performance in transcritical cycles in refrigeration mode is the coupling of elements to the cycle. Thus, this paper presents the analysis of configurations for achieving an increase in the performance, and in order to achieve it, it is proposed to include an internal heat exchanger, an ejector and a turbine. Both the ejector and the turbine have been considered as a solution for the irreversibilities that are produced in the expansion stage during the cooling cycle. A comparison among the three proposals is carried out, and the adequate operational conditions to which it is recommended to use one or other configuration are analyzed. The results show that the use of the ejector is recommended for output temperatures above 27 °C in the gas cooler. By doing this, an increase in the coefficient of the energy performance was achieved, which is superior to the one obtained when an intermediate heat exchanger is used. Finally, the increase in the COP as a function of the evaporation technology in each cycle is higher in the analyzed proposals, in which the increase reached is 35.85% when using an ejector, 24.21% when using a turbine, and 25.74% when using the internal exchanger. All of the configurations have been simulated under conditions of medium temperature refrigeration.

1. Introduction

In view of the fact that global warming is a reality, the use of refrigerants with a lower potential of global warming and null potential of stratospheric ozone destruction is the set tendency for the following years in cooling and air-conditioning systems [1]. With this in mind, one of the natural refrigerants that have been increasingly gaining position in the world is CO_2, which now has a presence in subcritical and transcritical systems [2]. In particular, subcritical systems have their application in both multi-stage and cascade systems, and it has been proven that the energy performance, COP, reached with this application is truly effective. On the contrary, when CO_2 is used in the transcritical cycle and in refrigeration mode, the performance of the system is low in comparison with the use of conventional refrigerants.

Some investigators have theoretically evaluated the performance of the transcritical cycle through different configurations [3–5] and concluded that the increase in COP can be mainly achieved in two ways: by modifying the expansion stage or by introducing an internal exchanger.

In the first modification, the proposal is aimed to replace the device of conventional expansion; this is because the highest irreversibility is presented during the expansion stage. Among the most common devices are the use of a turbine and an ejector. Both

* Corresponding author. Tel.: +524566437180 x136; fax: +524566437180 x137.
E-mail address: vperezgar@utsoe.edu.mx (V. Pérez-García).

http://dx.doi.org/10.1016/j.applthermaleng.2016.01.092
1359-4311/

configurations comparing the conventional system have resulted to be satisfactory by increasing the COP by 44% for the turbine configuration and by 35% when using the ejector [6,7]. When using an internal heat exchanger, IHX, as an adequacy for the cycle, the theoretical energetic performance increases by 24% [8]. While in an experimental basis the results show an increase in the COP of 10.6% [9,10], in view of the fact that the position of the IHX in the cycle is another variable to increase the energy performance in the system. Other publications [11–13] have focused on the combination of the intermediate heat exchanger and ejector, or the internal heat exchanger and turbine, and they have concluded that when including an internal heat exchanger in a cycle operating with ejector or turbine, far from increasing the COP, the internal heat exchanger reduces the energy performance of the cycle. Because of this, it is not recommended to perform transcritical cycles by combining an internal heat exchanger with an ejector or a turbine.

Although the mentioned modifications to the transcritical cycle have been analyzed by a great number of authors, there is not an analysis that presents the differences among each of these configurations or the evaporation temperature range in which a determined configuration can be more efficient than the other. Thus, in this paper the following configurations are compared:

a) Transcritical cycle with internal heat exchanger,
b) Transcritical cycle with ejector, and
c) Transcritical cycle with turbine

These configurations have been evaluated theoretically for similar working conditions and compared against the conventional transcritical cycle. Moreover, an analysis of the energy performance among both configurations was done, with the aim of showing the conditions under which the use of the ejector as the internal heat exchanger can be beneficial. The analysis was performed at a medium temperature under the same working conditions.

2. Working conditions

The objective of this study is to perform a theoretical comparison among the three alternatives found in transcritical cycles in order to find improvements in the COP of the basic cycle. Table 1 presents the operation conditions in which the transcritical cycle is simulated for the configurations already mentioned. In all cases, the operational conditions were obtained from the literature [11–13]. Such conditions are for applications in medium temperature refrigeration [14].

3. Schemes that improve the COP

Fig. 1 shows the transcritical cycle with turbine along with its representation of behavior in a diagram *ph*; some investigators [15,16] describe this configuration as the most efficient because, with the use of this element in the expansion stage, the work produced by the turbine can be used in the compressor and therefore reduce the power supply. Moreover, the irreversibilities are reduced by 7%

Table 1
Operating conditions of transcritical cycle.

Parameter	Value
Evaporating temperature	−10 °C
Gas cooler temperature outlet	35 °C
Isentropic efficiency of the compressor	0.75
Isentropic efficiency of the turbine	0.75
Heat exchanger effectiveness	0.5
Nozzle efficiency	0.85
Diffuser efficiency	0.85

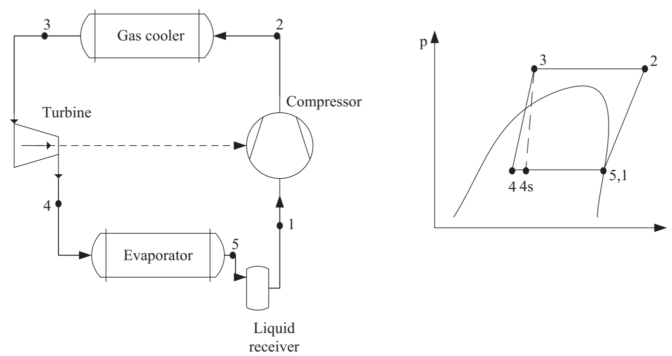

Fig. 1. Work recovery cycle.

when comparing the cycle with a conventional one that uses an expansion valve. Sarkar [3] claims that this configuration is optimal; energetically speaking, nonetheless, it is quite expensive to do it in practice.

However, Fig. 2 shows a cycle in which the turbine has been replaced by an ejector, which is an element without moving parts that allows expanding the refrigerant through momentum transfer. The ejector, in comparison with the turbine, is a dispositive that operates according to the thermo-compression's principle. Its geometry is axial and symmetric; it is formed by a main nozzle, a section for mixing, and a diffuser. The operation of the ejector is determined by the entrainment ratio, μ, which is defined as suction mass flow rate in Eq. (3) divided by motive mass flow rate in Eq. (8), i.e.

$$\mu = \frac{m_2}{m_1} \tag{1}$$

This depends on the pressures from the motive and suction streams, besides the discharge pressure in the equipment. Some investigators [17–19] have evaluated the performance of this element by varying the pressure conditions and they have achieved increases in the COP by 21% in comparison with the simple cycle.

Finally, Fig. 3 shows the cycle with an internal heat exchanger which is one of the most currently used modifications in search of an increase in the COP. Through the implementation of this equipment the degree of sub-cooling is increased, as shown in the diagram *ph* in Fig. 3 (processes 3–4) at the outlet of the gas cooler, which thermodynamically produces an increase in the cooling capacity. The authors [20,21] have shown the advantages of the heat exchanger inside a transcritical cycle. Furthermore, experimentally, in He et al.'s [22] report the inclusion of this equipment increases the performance of the refrigeration cycle by up to 11% with respect to the configuration of conventional cycles.

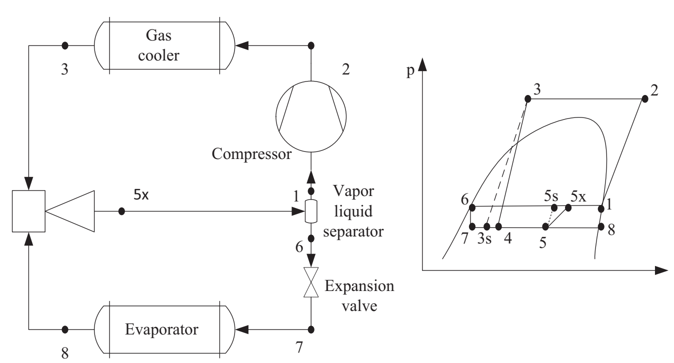

Fig. 2. Ejector cycle.