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Research Paper

Numerical investigation of CO_2 behavior in the internal heat exchanger under variable boundary conditions of the transcritical refrigeration system

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HIGHLIGHTS

- This paper provide detailed information on the transient behavior of CO_2 in the IHX.
- 5 different boundary conditions during the start-up of a refrigeration system were analyzed.
- The numerical simulation is carried out using CFD code FLUENT.
- Transient behaviors of the IHX heat transfer rate and thermal effectiveness were discussed.
- The transient behavior of COP was analyzed.

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ABSTRACT

The study is focused on the impact of the variation in temperature and mass flow at the inlet boundary of both hot and cold streams, on the CO_2 thermophysical properties, the heat transfer rate and thermal effectiveness of an internal heat exchanger, and therefore the overall coefficient of performance of a transcritical refrigeration system. Five different cases of boundary conditions based on temperature and mass flow rate are numerically analyzed using the commercial Computational Fluid Dynamics software Fluent. The governing equations are discretized by using the finite volume method. Numerical results were successfully compared with empirical correlations for the Nusselt number. Additionally, the effect of mesh density on the numerical results was analyzed. The results showed that the hot stream is the most affected by the transient change due to the supercritical operating conditions. The change in the mass flow rate causes the decrease in the heat transfer rate and the thermal effectiveness at the beginning of the system operation. The transient period of both heat transfer rate and the thermal effectiveness extends much more when the inlet temperature is low. The high inlet temperature allows the internal heat exchanger to be more efficient. The transient behavior of the coefficient of performance is inversely proportional to that of the internal heat exchanger thermal effectiveness.

1. Introduction

In recent decades, CO_2 has been reintroduced into the field of refrigeration, air conditioning and heat pumps as refrigerant for solving the problem of global warming caused by refrigerants belonging to the family of HFCs. CO_2 is one of the few natural refrigerants, which is neither flammable nor toxic. It is inexpensive, widely available and does not affect the environment as many other refrigerants. In addition, it has better thermophysical properties such as a low viscosity, a high specific heat, a high volumetric heat capacity and a high thermal conductivity, compared with conventional refrigerants [1–3]. In the field of refrigeration and air conditioning systems, the use of CO_2 as working fluid, especially in transcritical systems, represents low performance due to the huge expansion loss when compared with conventional systems [4–7]. This deficiency has attracted the attention of several researchers, who have performed some studies that have been carried out in order to improve the coefficient of performance, COP. Among the main research fields, the modification of the basic cycle

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Nomenclature

CA	thermal capacitance (W/K)
Cp	specific heat (J/kg K)
D	dimension
eff	thermal effectiveness
g	gravitational acceleration (m/s^2)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
Q	heat transfer (W)
T	temperature (K)
t	time (s)
v	velocity (m/s)
$\dot{W}$	mechanical power of the compressor (W)
x	direction (m)
y	direction (m)
z	direction (m)

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
∇	nabla symbol
λ	thermal conductivity (W/m K)
ϕ	angle (°)

Subscripts

i	coordinate index in x direction
j	coordinate index in y direction
IHX	internal heat exchanger
k	coordinate index in z direction
max	maximum
min	minimum
t	turbulent
$1,6$	thermodynamic states of the cold stream
$3,4$	thermodynamic states of the hot stream

Superscript

c	cold
h	hot

configuration of the system has been the most developed theme, experimentally and theoretically. It can be found, for example, works performed on the use of two-stage compression systems to enhance the compression process [4–10], the use of a turbine or an ejector to recover the expansion work [11–14], and the insertion of an internal heat exchanger, IHX, in the basic transcritical cycle [15–21]. For instance, Lorentzen and Pettersen [21] were the first researchers who proposed the use of an IHX in the basic transcritical cycle. Boewe et al. [22] indicated up to 25% improvement in the COP, as compared to the cycle without IHX. Rozhentsev and Wang [23] reported that the COP may decrease when the size of the internal heat exchanger is high. Mu et al. [24] showed that IHX with a wide capacity can lower the optimum high-side pressure. Yamasaki et al. [15] proved through an experimental study that the IHX improves the efficiency of the refrigeration cycle. Sarkar et al. [3] showed that the use of an IHX may be profitable at higher refrigerant temperatures at the gas cooler exit. Bhattacharyya et al. [25] reported that the effect of an IHX on system performance and optimum discharge pressure is negligible at low and moderated refrigerant temperatures at the gas cooler exit; however it becomes more significant at high refrigerant temperatures at the gas cooler exit. Chen and Gu [26] derived a practical effectiveness expression for IHX and reported theoretically that an IHX with high effectiveness is an important factor in achieving a high cycle performance. Thus, contribution of IHX to improve COP has been reported in several works [27–29].

Despite all the efforts provided by studies demonstrating how the use of IHX can bring solutions to the problem of lower transcritical refrigeration system performance, some aspects need to be investigated and understood more broadly, such as the transient behavior of the IHX during the start-up of the system. Since CO_2 coming out of the gas cooler enters into the IHX at supercritical pressure and temperature, causes significant variations in the CO_2 thermophysical properties [30–34], especially during the start-up of transcritical refrigeration systems when the system is subjected to instability of operating conditions. This transient behavior can be analyzed and predicted through a numerical simulation of the IHX. Some studies have addressed this issue without further details. For instance, Kim et al. [35] performed an experimental and numerical study on heat transfer and pressure drop characteristics of an IHX in transcritical CO_2 systems. Despite the interesting results obtained, only the steady state behavior of heat transfer and pressure drop was analyzed. Rigola et al. [19] investigated numerically and experimentally the influence of using an IHX in order to improve the transcritical cycle performance. Although a transient model based on the global algorithm was used for numerical simulation, no results in the transient period have been shown.

This paper provides detailed information on the transient behavior of CO_2 in the IHX under five different boundary conditions during the start-up of a transcritical refrigeration system. The inlet temperature and mass flow rate are the main boundary conditions based on which this analysis is performed since they are the most sensitive operating conditions in the CO_2 transcritical system. The main contribution of this work is that it shows in detail how transient changes in temperature and mass flow rate at the inlet of both hot and cold IHX streams can affect the behavior of all thermophysical properties of CO_2 as well as the heat transfer parameters in the IHX. In addition, it can be seen the transient effects of both boundary conditions on the IHX heat transfer rate and thermal effectiveness, and therefore on the COP of the transcritical system. The analysis is performed using a 3D model in order to have more information about the behavior of the heat transfer parameters in the whole volume of each domain. The numerical simulations are carried out using the commercial Computational Fluid Dynamics (CFD) code FLUENT.

2. Geometric model description

The internal heat exchanger under study is a horizontal tube-in-tube heat exchanger, designed for an experimental refrigeration facility whose sketch is presented in Fig. 1a. It is a counterflow heat exchanger (Fig. 1b) constituted of twelve inner tubes (Fig. 1c) through which CO_2 coming from the gas cooler flows under supercritical conditions. These tubes are enclosed in an annular tube (Fig. 1d) wherein the CO_2 flows in the opposite direction, under subcritical conditions coming from the evaporator. The IHX characteristics are described in Table 1.

The geometric model is built in 3D using the ANSYS DesignModeler tool, from the ANSYS Workbench platform, according to the characteristics of the experimental IHX, and taking into account the following considerations to reduce the complexity of the model: