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Comparative analysis of a concentric straight and a U-bend gas cooler configurations in CO_2 refrigeration system

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A B S T R A C T

This paper compares the heat transfer performance of two gas cooler configurations using CO_2 as refrigerant. Straight gas cooler *vs* U-bend gas cooler was analyzed using 3D numerical simulation employing ANSYS FLUENT commercial program. The importance of the structure of the mesh was discussed and the unstructured sweep method was selected. Numerical results were satisfactorily compared with those of eight different empirical correlations for the Nusselt number applicable to similar heat exchangers. Behaviors of the local CO_2 thermophysical properties, turbulence parameters, and heat transfer parameters in both straight and U-bend gas cooler configurations were analyzed. The results of this analysis were used to predict the transient behavior of the heat transfer rate and the thermal effectiveness of the two configurations. An increase of 16% was observed in the thermal effectiveness of the gas cooler based on U-bend configuration compared to the straight gas cooler configuration. Finally, the transient behavior of the overall efficiency of the transcritical refrigeration facility in which the two gas cooler configurations are supposed to be installed was assessed. The installation based on U-bend gas cooler geometry has presented higher performance of about 20% of efficiency when compared with the straight geometry.

1. Introduction

Heat exchangers are key components in the operation of a refrigeration system. A better understanding of their thermal and hydrodynamic behavior is important in order to improve performance and to select a design. In the transcritical refrigeration system, the gas cooler is the main heat exchanger in which variations in its operating conditions affect largely the coefficient of performance, COP, of the system due to the instability in the thermophysical properties of the refrigerant (CO_2) in the pseudo-critical region [1]. For instance, in this region, the specific heat of CO_2 reaches its maximum value. This increase causes a growth of the heat transfer rate, then forces the gas cooler to have a greater heat transfer area, and therefore leads to a reduction in the overall cycle efficiency [2]. On the other hand, the thermal effectiveness of the gas cooler is also affected by the environmental temperature [3]. A rise in environmental temperature may cause an increase in the input temperature of the gas cooler secondary fluid, which can affect the outlet CO_2 temperature, and therefore leading to a reduction of the COP [4–6]. Another factor that can affect the COP of transcritical refrigeration system is the gas cooler geometry. Some experimental and theoretical studies have been conducted on the improvement of COP by modifying conventional straight the gas cooler geometry. For instance, Gupta and Dasgupta [6] introduced a mathematical model for air cooled finned tube gas cooler, which was validated and used for the performance analysis under various design and operating conditions. With this model is possible to design guidelines for optimized performance of a gas cooler at different ambient temperatures. Park and Hrnjak [7] investigate the effect of conduction through the fins on the capacity of a serpentine gas cooler. The simulation results of the gas cooler capacity model were validated with experimentally measured capacity. They conclude that COP could improve by 5% by eliminating the severe conduction effect. Ge and Cropper [8] developed a mathematical model of a finned-tube air-cooled CO_2 gas cooler, this model used a distributed method to predict accurately the thermophysical properties and local heat transfer coefficient during gas cooling process. Additionally, the authors explored the maximum system operating efficiency.

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Nomenclature

Cp	specific heat [kJ/kg K]
D	dimension
g	gravitational acceleration [m/s^2]
P	pressure [Pa]
T	temperature [K]
t	time [s]
v	velocity [m/s]
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
k	coordinate index in z direction
t	turbulent

As can be observed in the previous literature, the majority of the researches were performed on the finned coil heat exchangers. However, the main disadvantages of this type of heat exchangers are the high-pressure drop inside the coil due to the high number of passes, and the lower heat transfer coefficient on the air side. These two main drawbacks limit the use of this heat exchanger in large installations. The best alternative to the finned coil heat exchangers can be the concentric U-bend heat exchanger that uses a single tube or multi-tube within an annular tube. It is designed for a high-pressure service and is able to handle a large temperature difference between the annular and tube sides without using expansion joints. It produces turbulent conditions at low flow rates increasing the heat transfer coefficient and heat transfer rate [9]. This heat exchanger plays an important role in the improvement of the conventional refrigeration system performance. It is used as evaporator [9] and condenser [10] as well as in the geothermal heat pump [11], in heat exchangers using nanofluids [12], and in torus reactors [13].

Despite of the attractive advantages of a concentric U-bend heat exchanger, its use as a gas cooler in a transcritical refrigeration system is practically null. To the authors' knowledge, there are not experimental and theoretical studies in the literature based on the use of concentric U-bend exchanger as gas cooler.

In this paper a novel detailed information on the heat transfer parameters of a concentric U-bend gas cooler configuration by making a comparison with a straight-tube gas cooler configuration having the same geometric characteristics is carried out. The comparative analysis is based on transient 3D numerical simulations using ANSYS FLUENT commercial program. The result analyzed includes the CO_2 thermophysical properties, the turbulent energy parameters, the heat flux, the convective heat transfer coefficient and the thermal effectiveness. The study is not only limited to compare the thermal behavior of the two gas coolers configurations, also shows their impacts on the COP of the transcritical refrigeration system.

2. Description of the geometric models

The characteristics of the geometric models developed in this work are based on a horizontal concentric CO_2/water U-bend gas cooler designed for an experimental facility as shown in Fig. 1. The gas cooler is constituted of nineteen inner tubes (see Fig. 1b) through which CO_2 coming from the compressor flows under supercritical conditions. The inner tubes are enclosed in an annular tube (see Fig. 1c) wherein the cold water flows in the opposite direction, as subcooled liquid. The general dimensions of the experimental U-bend gas cooler are described in Table 1.

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

- Both geometric models are designed as tube-in-tube heat exchangers by considering an equivalent diameter (d_{eq}), which is the approximate inner diameter with a volume equal to that of the experimental component. It is calculated by the Eq. (1) [14].

$$d_{eq} = d \cdot N_{tb}^{0.5} \tag{1}$$

  where d and N_{tb} are the diameter of tube and the number of tubes, respectively.
- The domain of the annular tube is negligible because there is no heat loss to the environment, i.e., the experimental gas cooler is considered isolated.

Table 2 describes the geometric characteristics of both models.

Fig. 2 shows the concentric straight and U-bend geometric models. In Fig. 2a and b, the complete geometries are presented, while in Fig. 2c and d a front view of each model is shown. This allows the visualization of the three different domains including the CO_2 (1), the inner tube (2) and the water (3).

The meshes are performed in ANSYS Meshing. The unstructured sweep method with all tri free face mesh-type is chosen in order to have control on the cell size near the interfaces of the different domains. Fig. 3a and b show the mesh in real geometry size, while Fig. 3c and 3d show their front views.

The mesh independency of the results is verified by varying the mesh size as shown in Fig. 4. The temperature of the CO_2 is observed to perform the sensitive analysis of the mesh. This choice is due to the fact that temperature is the main operating condition in which a small change can significantly affect the behavior of the thermophysical properties and therefore the heat transfer rate [1]. The analysis is performed using six different mesh sizes as shown in Fig. 4a and b. The results are presented in a spatial graphic for testing the mesh quality at different locations. The results show that the profiles of the temperature are no longer influenced by the mesh sizes when the number of mesh elements is above 478800 for the straight model (see Fig. 4a), and larger than 886000 for the U-bend model (see Fig. 4b). In order to reduce the simulation time, those geometries were chosen for this study. The characteristics of the selected mesh sizes are presented in Table 3, where it can also be observed the quality control factors

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