Energy Conversion and Management 89 (2015) 92–98

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Modeling and calculation of open carbon dioxide refrigeration system

Yufei Cai, Chunling Zhu *, Yanlong Jiang, Hong Shi

College of Aerospace Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 30 June 2014
Accepted 21 September 2014

Keywords:
Carbon dioxide
Open refrigeration system
Refrigeration capacity loss
Supercritical state
Two-phase region

ABSTRACT

Based on the analysis of the properties of carbon dioxide, an open carbon dioxide refrigeration system is proposed, which is responsible for the situation without external electricity unit. A model of open refrigeration system is developed, and the relationship between the storage environment of carbon dioxide and refrigeration capacity is conducted. Meanwhile, a test platform is developed to simulation the performance of the open carbon dioxide refrigeration system. By comparing the theoretical calculations and the experimental results, several conclusions are obtained as follows: refrigeration capacity loss by heat transfer in supercritical state is much more than that in two-phase region and the refrigeration capacity loss by remaining carbon dioxide has little relation to the state of carbon dioxide. The results will be helpful to the use of open carbon dioxide refrigeration.

1. Introduction

CO_2 used as a refrigerant has attracted widely attention recently, because it is a natural refrigerant with environmentally friendly property [1]. CO_2 refrigeration systems can be divided into two types, open refrigeration systems and closed refrigeration systems. In a closed refrigeration system, CO_2 flows through compressor, gas cooler, throttle device, evaporator in sequence, and then comes back to the compressor again. In an open refrigeration system, CO_2 is throttled into low pressure and low temperature fluid. Then it flows into evaporator for evaporative refrigeration, and it released into environment ultimately. According to these two working processes, open refrigeration systems without external electricity unit are suitable for the cases of limited electrical power supply such as movable mine refuge chambers [2], food vehicles [3] and some disposable refrigeration systems. As the refrigerant flows out from the throttle device is two-phase fluid, the temperature of the refrigerant in the evaporator only depends on the pressure. The evaporator can be designed as a container, and some tests which need stable low temperatures can be carried out in the container. The shelf life of food can be extended in the case that CO_2 is released directly into food storage room [4] and these CO_2 is released to the environment finally.

Coal mine accidents have occurred frequently in recent years. According to the survey of the mine disasters around the world, only a few people die at the moment of disasters, whereas most people cannot escape and die from drowning, choking and poisoning [5]. Therefore, refuge chambers are proposed in order to provide miners a safety confined space when incidents happen. The refrigeration system is an important part of the environmental control system for underground rescue. As CO_2 is non-toxic, open CO_2 refrigeration systems have been widely used in refuge chambers for coal mine in China.

The previous studies on the CO_2 refrigeration systems mainly focused on the transcritical cycle [6–10] and cascade refrigeration systems [11–14], while open refrigeration systems are less reported. Yan developed an open refrigeration system in a refrigeration lorry [3,15] without considering the effect of storage environment of carbon dioxide on the refrigeration performance and the refrigeration capacity loss. During some design processes of open refrigeration systems, the needed mass of CO_2 was determined by experiment that made a lot of CO_2 wasted [16]. In this paper, a model of open CO_2 refrigeration system is developed and the parameters of the storage environment such as the temperature and the storage capacity are investigated. As shown in Fig. 1, the open refrigeration system discussed here includes two rooms, one is used for CO_2 storage and the other is used as air-conditioned room. In this system, the high pressure and normal temperature CO_2 first flows out of the tank when the manual valve is open, both of the pressure and temperature will slightly decrease. Then the CO_2 will flow through the throttle valve, the pressure and temperature will decrease greatly, and the cool CO_2 will flow into the evaporator to evaporate and absorb heat in the air-conditioned room. Finally the heated CO_2 will be released into the environment.

* Corresponding author. Tel.: +86 25 84896667; fax: +86 25 84892150.
E-mail address: clzhu@nuaa.edu.cn (C. Zhu).

http://dx.doi.org/10.1016/j.enconman.2014.09.061
0196-8904/

Nomenclature

A	surface area
h	enthalpy
H	height
m	mass
p	pressure
q	cooling load of the system
Q	quantity of heat
u	internal energy
v	specific volume
t	time
T	temperature
α	convective heat transfer coefficient
η	efficiency

Subscripts

bottom	bottom of the tank
ex	the CO_2 emission to the environment
eff	effective
ht	heat transfer
init	initial state in the tank
loss_ht	refrigeration capacity loss by heat transfer
loss_remain	refrigeration capacity loss by remaining CO_2
l	liquid CO_2
out	outside
s	saturated gas
surface	surface of the tank
tank	CO_2 remaining in the tank
0	total time

2. Calculation model

For open refrigeration systems, Eq. (1) is often used to calculate the mass of CO_2 roughly.

$$m = \frac{q}{h_{ex} - u_{init}} \Delta t \tag{1}$$

Eq. (1) does not consider the effect of refrigerant's state changing during the working process and the remaining CO_2 in the tank after working process. The temperature of the refrigerant in the tank will decrease when the refrigerant is released. That causes the heat transfer from ambient air to the refrigerant in the tank a, and results in the change of the refrigerant's enthalpy ultimately. Therefore Eq. (1) is only applied in the initial calculations.

This paper presumes that the heat exchange between CO_2 in the evaporator and the air in the room is sufficient. Since the wall of tank is relatively thin, the thermal resistance of the tank is ignored. This paper mainly focuses on the effect of the change of CO_2's state in the tank and the loss of the refrigeration capacity on the refrigeration performance. And the initial temperature of CO_2 in the tank is equal to the ambient temperature. In open refrigeration systems, the calculation condition can be divided into two-phase regions and single-phase regions.

2.1. Single-phase model

Ignoring the effect of gravity, CO_2 is presumed to be uniform. Eqs. (2)–(4) are volume conservation equation, mass conservation equation and energy conservation equation respectively.

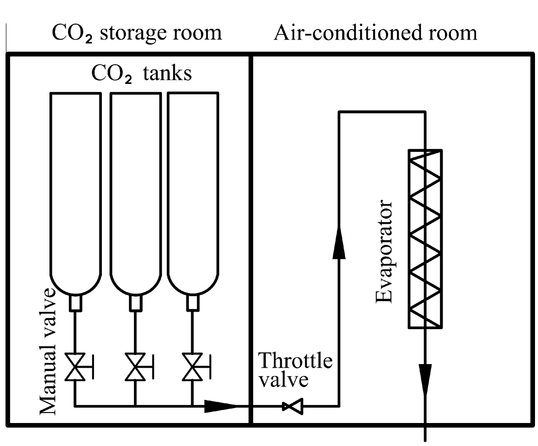

Fig. 1. CO_2 open refrigeration system. The arrows represent the flow direction of CO_2.

$$\frac{d(mv)}{dt} = 0 \tag{2}$$

$$\frac{dm}{dt} = \frac{q}{h - h_{ex}} \tag{3}$$

$$\frac{d(mu)}{dt} = \alpha_{out} A_{eff} (T_{out} - T) + h \frac{dm}{dt} \tag{4}$$

2.2. Two-phase model

In the two-phase model, the liquid is at the bottom due to the effect of gravity. So, the flowing out CO_2 is in liquid state as the CO_2 tank stands upside down. The mass and energy conservation equations can be written as follows:

$$\frac{dm}{dt} = \frac{q}{h_l - h_{ex}} \tag{5}$$

$$\frac{d(mu)}{dt} = \alpha_{out} A_{eff} (T_{out} - T) + h_l \frac{dm}{dt} \tag{6}$$

2.3. Solution Procedure

Considering of the similarity of the formulas for the single-phase and two-phase models, only the latter is analyzed here. Decomposing the Eqs. (2) and (6), Eqs. (7) and (8) are obtained.

$$m \frac{dv}{dt} + v \frac{dm}{dt} = 0 \tag{7}$$

$$m \frac{du}{dt} = \alpha_{out} A_{eff} (T_{out} - T) - (u - h_l) \frac{dm}{dt} \tag{8}$$

Substitute the Eq. (5) into (7) and (8), Eqs. (9) and (10) are obtained.

$$\frac{dv}{dt} = -\frac{v}{m} \cdot \frac{q}{h_l - h_{ex}} \tag{9}$$

$$\frac{du}{dt} = \frac{1}{m} \left[\alpha_{out} A_{eff} (T_{out} - T) + \frac{h_l - u}{h_l - h_{ex}} q \right] \tag{10}$$

The single phase model can be obtained in the same way.

$$\frac{dv}{dt} = -\frac{v}{m} \cdot \frac{q}{h - h_{ex}} \tag{11}$$

$$\frac{du}{dt} = \frac{1}{m} \left[a_{out} A_{eff} (T_{out} - T) + \frac{h - u}{h - h_{ex}} q \right] \tag{12}$$