Applied Thermal Engineering 52 (2013) 304–312

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Study on open-cycle carbon dioxide refrigerator for movable mine refuge chamber

Yang Junling [a,b], Yang Luwei [a,*], Wei Juan [a,b], Ma Yuezheng [a], Zhang Zhentao [a]

[a] Technical Institute of Physics and Chemistry of CAS, 29 Zhongguancun East Road, Haidian District, Beijing 100190, China
[b] Graduate University of CAS, Beijing 100049, China

HIGHLIGHTS

► Carbon dioxide open cycle cooling is proved suitable for mine refuge chamber.
► Stainless steel fin heat exchanger shows same performance to normal copper one.
► Long capillary tube heat exchanger avoids frosting and blocking effectively.

ARTICLE INFO

Article history:
Received 25 August 2012
Accepted 14 December 2012
Available online 27 December 2012

Keywords:
Carbon dioxide
Open-cycle refrigerator
Mine refuge chamber
Capillary tube
Heat exchanger

ABSTRACT

For a movable mine refuge chamber, the refrigeration system is important to remove miners' body heat and the heat input from the hot outside environment. The refrigeration cycle has been changed from closed cycle using traditional Freon refrigerant to open cycle using high pressure carbon dioxide. The open cycle refrigerator has no compressor and it consumes no electricity. The open system is composed of a Joule–Thomson (JT) valve, an evaporator, a capillary heat exchanger, a pneumatic blower and several connecting tubes. For the evaporator, a stainless steel heat exchanger as well as a smooth tube heat exchanger were designed and tested and compared with a conventional finned tube copper heat exchanger. The tests show that the performance of cooling and dehumidification is nearly the same for the three heat exchangers. Because the stainless heat exchanger has higher strength and lower cost than the two others, it might be the best choice in actual applications. A long capillary tube heat exchanger is used to decrease the carbon dioxide pressure from around 20–35 bar to 5 bar, and at the same time the gas is kept above a temperature of 10 °C by making use of the sensible heat.

1. Introduction

Movable mine refuge chambers are used to shield miners who fail to escape from the mine when incidents occur. Such movable refuge chambers are sealed ones that are made of steel. They should provide breathable air, food, water and a safe environment for up to 96 h.

Refuge chambers will be hot and humid, depending on the internal as well as the environmental conditions. The US federal law states that the apparent temperature in a fully occupied refuge chamber shall not exceed 35 °C [1]. The apparent temperature is considered as a measure of discomfort taking into account the combined effects of air movement, heat, and humidity on the persons inside the chamber. Based on engineering tests it is likely that the apparent temperatures will lead to evident discomfort when it approaches 35 °C [2]. High levels of heat and humidity can cause sweating, paleness, cramps, tiredness, weakness, dizziness, headache, nausea or vomiting, and fainting [3]. A refrigerator in the movable mine refuge chamber for controlling heat and humidity is a fundamental requirement.

As shown in Fig. 1, the traditional air-conditioner mainly consists of a condenser, an evaporator, a compressor, and a throttle valve. But the compressor should not be used in a coal mine. On the one hand, in most situations the electric power supply breakdown will occur at an accident, and the refrigerator will fail to run. On the other hand, the compressor is located outside of the refuge chamber, and could be damaged by gas explosions that often occur in underground coal mines. Therefore, as illustrated in Fig. 2, the open cycle refrigerator is preferred, since no compressor is needed. In the open cycle refrigerator the refrigerant gas is compressed, condensed to liquid, and then stored in the cylinders. In case of an

* Corresponding author. Tel.: +86 (0)1 62627901; fax: +86 (0)1 82543446.
E-mail addresses: ww_yang@yahoo.com.cn (Y. Junling), lwyang2002@yahoo.com.cn (Y. Luwei).

1359-4311/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2012.12.014

Nomenclature

d	diameter (mm)
h	specific enthalpy (J kg^{-1})
Nu	Nusselt number
Pr	Prandtl number
T	temperature (°C)
v	velocity (m s^{-1})
ε	internal surface roughness (mm)
g	mass flux (kg m^{-2} s^{-1})
L	capillary tube length (mm)
p	pressure (bar)
Re	Reynolds number
U	heat transfer coefficient (W m^{-2} K^{-1})
α	heat transfer coefficient (W m^{-2} K^{-1})
λ	heat conductivity (W m^{-1} K^{-1})

accident, the pressure of the refrigerant is reduced, thereby using evaporation for the refrigeration process. Then the gas is exhausted to the environment. Here the refrigerant is not recyclable. Therefore a sufficient quantity should be stored, which will occupy much space. So the selection of a non-toxic working fluid with large cooling capacity is important.

The common refrigerants include R12, R22, R134a, NH_3 and CO_2. For a given cooling capacity, the volume of NH_3 is the smallest, followed by R22 and R134a, while the largest volume is needed for R12 and CO_2. As we know, NH_3 is toxic, and therefore it is dangerous in case of leakage. So NH_3 should not be used. In recent years, CFCs and HCFCs refrigerants gradually came out of use in the refrigerant industry. CO_2 exists naturally and can be captured from industrial processes. Since it is chemically stable, non-flammable and has a relatively low GWP (Global Warming Potential), it is treated as one of the next generation refrigerants. For these reasons, though with largest volume, CO_2 is the best choice in this open refrigeration cycle for underground applications.

The heat exchanger is the key component of the refrigeration cycle. The first CO_2 finned-tube heat exchanger was designed and manufactured at the Norwegian University of Science and Technology [4] and was used in motor vehicle air conditioning systems. At present, CO_2 refrigerator can also be used in residential air conditioning [5] and in heat pumps [6]. The favorable heat transfer properties of CO_2 enable a small heat exchanger area at the refrigerant side. So the air side is of main importance for the heat exchanger design. Finned-tube [7], plate, shell and tube [8], plate fin and micro channel heat exchangers [9] have already been designed and tested. But in the market, these heat exchangers are not generally available. For the present open cycle, it is very

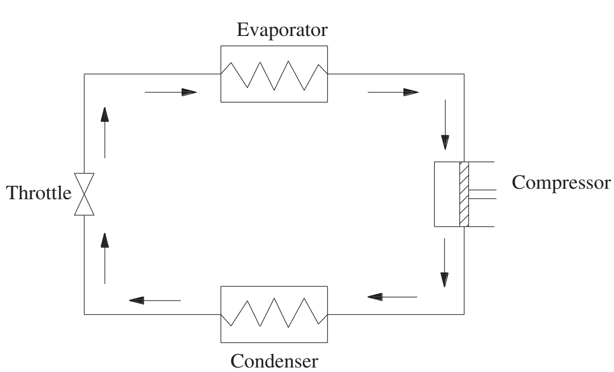

Fig. 1. An ordinary refrigerator.

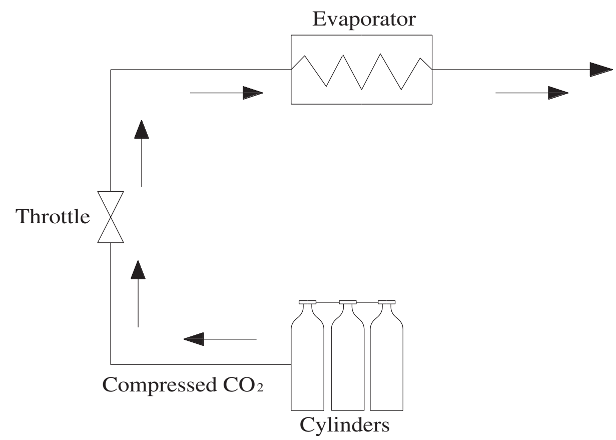

Fig. 2. An open cycle refrigerator.

important that the heat exchangers can withstand high pressures. Therefore, the stainless steel heat exchanger and the smooth copper tube heat exchanger are employed. The results are compared with the conventional finned tube heat exchanger made of copper.

The throttle valve and capillary tube are usually used to reduce pressure. For CO_2, the temperature decreases sharply when the pressure is below 20 bar. For a throttle valve, the process is adiabatic, and the temperature will drop to below 0 °C in a very short time, and the valve may be blocked. Traditionally, heat transfer in capillary tube has not been considered, when the capillary tube is very small [10–13]. However, the mechanism of capillary heat exchanger has been studied experimentally and numerically by several authors [14–17]. In this research, the capillary tube is used as a heat exchanger in the open cycle refrigerator. The heat transfer performance is analyzed by experiment and simulation.

The published research about the open refrigeration cycle with CO_2 is quite few. Cai Y.F. [18] discussed the effect of the storage condition on the cooling capacity in the open refrigeration cycle and shown that the loss of refrigeration capacity is larger in supercritical state. Yan and Tong [19] researched on the possibility for aquatic product preservation with open-cycle CO_2 refrigeration.

In the present paper, the experimental investigation of this type of refrigeration cycle is reported.

2. Analysis and design of the refrigeration cycle

2.1. The refrigeration process

The test system, as shown in Fig. 3, includes cylinders with liquid CO_2 (50–70 bar), throttle valve, evaporator (first heat exchanger), capillary tube heat exchanger or alternatively valve plus heat exchanger (second heat exchanger), and a pneumatic blower. In order to extract the liquid CO_2, siphons are inserted in all cylinders and the liquid flows through the siphons when the valves are opened. The outlets of all cylinder valves are connected to a common tube that is connected to the throttle valve. The throttle valve controls the inlet pressure of the evaporator, which varies from 20 bar to 35 bar corresponding to evaporation temperatures of −10 to 7 °C, respectively. After the first heat exchanger, the CO_2 changes from saturated liquid to overheated gas. When flowing through the capillary tube heat exchanger, the CO_2 stays an overheated gas. The black bold line of JT valve is another way to obtain a lower pressure. Then the gas flows into the pneumatic motor to drive the blower. Finally the CO_2 gas flows out of the refuge chamber at about 20 °C. The pneumatic blower is essential for the