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Research paper

Effects of lubricating oil on thermal performance of water-cooled carbon dioxide gas cooler

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HIGHLIGHTS

- A water-cooled CO_2 gas cooler model was developed and validated to consider the effects of lubricating oil.
- The negative effects of lubricating oil are more significant for gas coolers with small diameters ($D_h \leq 2$ mm).
- Lubricating oil reduces the thermal performance more as the operation pressure approaches the critical pressure.
- High thermal effectiveness can be achieved at a proper water flow rate, but lubricating oil clearly has a negative effect.

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ABSTRACT

A water-cooled concentric gas cooler model was developed to examine the negative effects of the presence of polyalkylene glycol (PAG)–type lubricating oil on convective heat transfer. The model was used to analyze the gas cooler performance in detail at different oil concentrations, tube diameters, operation pressures, mass flow rates, and inlet temperatures on the water side. The results show that the entrained lubricating oil had a dominant negative effect on gas coolers with a diameter of less than 2 mm. For CO_2 heat pump/refrigeration systems equipped with water-cooled micro- or mini-channel gas coolers, the lubricating oil retained in the heat exchanger should be minimized. The negative effects of the lubricating oil are dominant for a wide range of operation pressures. However, the deterioration in thermal performance becomes more apparent as the pressure approaches the critical pressure value. Proper determination of the coolant fluid mass flow rate increases the thermal effectiveness of the gas cooler for a wide range of water inlet temperatures, but the reduced heat transfer performance is more pronounced at higher mass flow rates.

1. Introduction

Increasing concern over protecting the environment has led to the reconsideration of refrigerants in refrigeration and air-conditioning systems. Because they deplete the ozone layer, hydrochlorofluorocarbons (HCFCs) currently in use are being phased out as per international agreement. Hydrocarbons (HFCs) are an alternative, but they have high global warming potential (GWP), so their application faces restrictions in the future. Among the efforts to find a suitable low-GWP substitute, carbon dioxide (CO_2) is considered to be a promising alternative for heat pump devices that provide domestic hot water, work as a standalone water heater, or are coupled with a chiller [1–4]. CO_2 is a nonflammable and nontoxic natural working fluid with zero ozone depletion potential (ODP) and negligible GWP. Moreover, it has favorable thermodynamic and transport properties, low cost, and high availability.

In contrast to traditional working fluids, CO_2 has a relatively low critical temperature (31.1 °C) but a rather high critical pressure (7.38 MPa). Therefore, when it rejects heat to the outside in the summer, CO_2 is in supercritical state with a continuously decreasing temperature in the gas cooler. Compared to the condensation process in traditional cycles, the CO_2 temperature profile matches that of the secondary fluid well; this decreases the

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Nomenclature

A	area (m^2)
c_p	specific heat capacity (kJ/kg K)
D	diameter (m)
f	friction factor (–)
G	mass flux (kg/m^2 s)
h	specific enthalpy (kJ/kg)
i	ith finite volume (–)
L	length (m)
m	mass flow rate (kg/s)
n	number of data points (–)
Nu	Nusselt number (–)
Pr	Prandtl number (–)
p	pressure (MPa)
Q	heat exchange capacity (kW)
q	heat flux (kW/m^2)
R	thermal resistance (K/W)
Re	Reynolds number (–)
T	temperature (°C)
U	overall heat transfer coefficient (kW/m^2 K)
w	element of weight matrices (–)

Greek symbols

α	heat transfer coefficient (kW/m^2 K)
ε	thermal effectiveness (–)
λ	thermal conductivity (W/m K)
ω	oil mass concentration (–)

Subscripts

act	actual
app	approach
b	bulk
CO_2	carbon dioxide
cal	calculated
cir	critical
exp	experiment
f	fluid
h	hydraulic
in	inlet
max	maximum
out	outlet
pc	pseudo-critical
r	ratio
ref	reference
spe	specified
w	water
wall	wall

Acronyms

ANN	artificial neural network
GWP	global warming potential
HCFCs	hydrochlorofluorocarbons
HFCs	hydrofluorocarbons
ID	inner diameter
LMTD	logarithmic mean temperature difference
MAE	mean absolute error
ODP	ozone depletion potential
OD	outside diameter
PAG	polyalkylene glycol
ε-NTU	effectiveness-number of transfer unit

irreversibility of the heat transfer process and improves the heat transfer efficiency [5]. With the temperature glide in the gas cooler, the water heater can produce hot water with a temperature of as high as 90 °C [6].

In the past decade, many experimental or theoretical studies have examined the overall performance of gas coolers cooled by either air or water [7–25]. Wang and Hihara [21] first developed a numerical model to simulate a counter-flow concentric gas cooler. They analyzed and compared the distributions of the local heat transfer coefficient, heat flux, and CO_2 bulk temperature along the axial direction of the gas cooler from different prediction models. Fronk and Garimella [22,23] conducted an experimental study on the performance of a compact water-coupled CO_2 micro-channel gas cooler and developed an analytical model. They indicated that, for the water-cooled CO_2 cooler, the refrigerant-side resistance is the dominant limiting factor in the heat transfer process. Yu et al. [24] set up a heat exchanger model to investigate the heat transfer behavior of a CO_2 tube-in-tube water-cooled gas cooler. Their calculations showed that the inlet pressure influences the overall heat transfer coefficient and variation in CO_2 temperature. Sánchez et al. [25] developed a model of a water–CO_2 coaxial gas cooler based on the finite volume method that they validated through experiments; they then used the model to examine the influences of operation parameters such as the CO_2 pressure, water mass flow rate, evaporating pressure, and water inlet temperature on the thermal effectiveness of a gas cooler. However, the calculation results using effectiveness-number of transfer unit (ε-NTU) methodology showed a large deviation with the experimental data.

For a water-cooled gas cooler, the CO_2-side thermal resistance is much less or close to that of the water side [24], especially in the case of a micro-channel gas cooler [23]. Thus, the heat transfer and flow characteristics of supercritical CO_2 being cooled in tubes or channels are important to accurately determining the performance of a water-cooled CO_2 gas cooler.

Many experimental and theoretical studies have been performed to develop good heat transfer and friction methods for the cooling of supercritical CO_2 [26–38] and CO_2 with entrained lubricating oil [39–50]. In particular, Cheng et al. [51] gave a comprehensive summary of the heat transfer and flow characteristics of supercritical CO_2 being cooled in large- and small-scale channels. Wang et al. [52] performed an overview of the effects of lubrication on the heat transfer performance of CO_2. The above research showed that lubricating oil has a severe adverse influence on the heat transfer coefficients and pressure drops of supercritical CO_2 cooling.

In a practical transcritical CO_2 heat pump/refrigeration system, lubricating oil is used in the compressor for lubricating, sealing, cooling, and cleaning purposes. A small amount of lubricating oil entrained with the refrigerant also flows in the system and can be retained in the heat exchangers. Hwang et al. [53] experimentally measured the oil retention ratio in the suction line, evaporator, and gas cooler of a CO_2 transcritical system at different CO_2 mass flow rates and oil concentrations. Their results showed that 2%–5% of the total oil volume was retained in the gas cooler at a CO_2 mass flow rate of 14 g/s and oil concentration of 1–5 wt%, which also resulted in a large pressure drop. Therefore, the influences of