INTERNATIONAL JOURNAL OF REFRIGERATION 56 (2015) 224–234

Available online at www.sciencedirect.com

ScienceDirect

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

Shell and tube carbon dioxide gas coolers – Experimental results and modelling

Claudio Zilio, Simone Mancin *

University of Padova, Department of Management and Technology, st.lla S. Nicola, 3, 36100, Vicenza, Italy

ARTICLE INFO

Article history:
Received 31 December 2014
Received in revised form
3 April 2015
Accepted 4 April 2015
Available online 15 April 2015

Keywords:
Shell and tube
Carbon dioxide
Heat pump
Gas cooler
Model

ABSTRACT

This paper experimentally compares the heat transfer performance of four different shell and tube gas coolers implemented in a 5 kW, R744 water/water heat pump controlled by a back pressure valve as expansion device. The tubes bundle consists of 10 tubes in a 30° arrangement for all the gas coolers with different tube geometries: smooth, corrugated, internally grooved, and corrugated and internally grooved, respectively. The results were carried out at fixed gas cooler inlet water temperature of around 25 °C and by imposing two inlet gas cooling pressures: 8 MPa and 10 MPa, and by varying the water flow rate from 340 to 786 l h^{-1}. A step-by-step procedure for the simulation of the heat transfer cooling process of the carbon dioxide in shell and tubes gas coolers is proposed and validated, allowing for a direct comparison of the heat transfer performance of the shell and tube gas coolers.

Refroidisseurs de gaz carbonique multitubulaires-Résultats expérimentaux et modélisation

Mots-clés : Multitubulaire ; Dioxyde de carbone ; Pompe à chaleur ; Refroidisseur de gaz ; Modèle

1. Introduction

According to the necessity of decreasing greenhouse effect, new fluids need to be investigated as refrigerants. Carbon dioxide has been demonstrated to be a viable option, because of its environmental friendliness, and some excellent thermodynamic and transport properties, such as high specific heat, high thermal conductivity, and low viscosity. Carbon dioxide operating according to a transcritical cycle is regarded as an energy efficient option for tap water heat pumps: the gas cooling process well fits the warming up of a finite stream of water, resulting in a quite large temperature lift in water without significant penalization in COP, as it was clearly demonstrated in the technical literature. In fact, Lorentzen (1994), Nekså et al. (1998), Nekså (2002), clearly explained of the benefits that can be derived by the use of CO_2 in heat pumps for tap water. The peculiar features of the transcritical cycle permit the use of once-through heat exchangers (gas coolers), where the R744 is cooled down by heating up the

* *Corresponding author*. Tel.: +39 0444 998746; fax: +39 0444 998788.
E-mail addresses: claudio.zilio@unipd.it (C. Zilio), simone.mancin@unipd.it (S. Mancin).
http://dx.doi.org/10.1016/j.ijrefrig.2015.04.006
0140-7007/

Nomenclature

A	area [m^2]
c_p	specific heat at constant pressure [$J\ kg^{-1}\ K^{-1}$]
d	diameter [m]
e_A	absolute deviation [%]
e_R	relative deviation [%]
h	enthalpy [$J\ kg^{-1}$]
K	overall heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
$\dot{m}$	mass flow rate [$kg\ s^{-1}$]
p	pressure [Pa]
q	heat flow rate [W]
R	thermal resistance ratio [-]
t, T	temperature [°C]
α	heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
σ_N	standard deviation [%]
Subscript	
CO_2	carbon dioxide
GC	gas cooler
e	external
H_2O	water
i	i-th element, inside
in	inlet
n	nominal
out	outlet
ss	shell side
ts	tube side

water. The gas cooling process needs to be investigated taking into account two points of view: the great variation of thermophysical properties and the large decrease in temperature occurring along the heat exchanger. In the last decades, several solutions have been proposed as gas coolers, among the most recent literature: tube-in-tube heat exchanger (HX) (Yu et al., 2012), helical coil-in-fluted gas cooler (Xu et al., 2011) finned coils (Hwang et al., 2005; Zilio et al., 2007; Ge and Cropper, 2009), air-cooled microchannel HX (Yin et al., 2001, Zhao and Ohadi, 2004), water-coupled microchannel HX (Fronk and Garimella, 2011a; 2011b).

All the above mentioned works proposed and experimentally evaluated simulation models of the relevant gas cooler types. Given the remarkable change of carbon dioxide thermophysical properties, all the Authors proposed a “distributed” approach: i.e. the heat exchanger is split in a number of small elements, so that the R744 properties change can be considered negligible through the single element. Hwang et al. (2005), Fronk and Garimella (2011b) used the Gnielinski (2006) equation for the calculation of the R744 local heat transfer coefficient, with the Filonenko equation for friction factor. Also Yin et al. (2001) and Xu et al. (2011) adopted the Gnielinski (2006) equation but the Churchill friction factor was used for the implementation. Ge and Cropper (2009) used the Pitla et al. (2002) approach with the Blausius friction factor. Yu et al. (2012) used the Dang and Hihara (2004) model for estimating the local supercritical carbon dioxide cooling heat transfer coefficient.

It is worth to highlight that the model proposed by Gnielinski (2006) was developed to calculate the single-phase liquid and gas heat transfer coefficients and it is not able to capture the effect of fluid properties change along the gas cooler tube cross section. Pitla et al. (2002) proposed a simple method to enable the Gnielinski equation to keep into account the properties change from the wall to the pipe core. Finally, the model suggested by Dang and Hihara (2004) was especially developed to estimate the heat transfer coefficients during the transcritical gas cooling process.

Zilio et al. (2007) compared the simulation results with Gnielinski (2006), Pitla et al. (2002), and Dang and Hihara (2004) of different air cooled finned coil gas coolers. Since the dominating thermal resistance during the tests was on the air side, they did not found relevant differences when using different equations for R744 heat transfer coefficient calculations. Emphasis was given in that work to the not negligible heat conduction through the aluminium fins.

More recently, many efforts have been dedicated to the modelling of different type of gas coolers, both liquid and air cooled. Among those, Sánchez et al. (2012) developed and validated a finite element model for water − CO_2 coaxial gas-coolers; Martínez-Ballester et al. (2013), Huang et al. (2014), Gupta and Dasgupta (2014) worked on the development of different models for air cooled microchannel and finned coil gas coolers and condensers.

Another still unexplored possibility is represented by the use of a shell and tube HX as gas cooler; this kind of heat exchanger in its various construction modifications is, undoubtedly, the most widespread and commonly used basic in the process industries, refrigeration, and air conditioning. It is also used in conventional energy production as condenser, feed water heaters, and steam generators for pressurized water reactor plants, and for many alternative energy applications including ocean thermal and geothermal. The reasons for this near-universal acceptance are several. Even if it is not very compact, nevertheless it is very robust and with its shape makes it suitable for high-pressure applications. The heat transfer area of a shell and tube heat exchanger can vary from less than 1 m^2 to 100,000 m^2 and it can operate from high vacuum to more than 1000 bar with temperatures, which can vary from cryogenics to 1400 K. All of these properties and features make the shell and tube heat exchanger an interesting candidate also for the R744 gas cooling process.

During the experimental campaign, four different water cooled shell and tube gas coolers implemented in water/water R744 heat pump were tested. The experimental measurements were carried out at two different gas cooling pressures: 8 MPa and 10 MPa, by varying the water flow rate at constant inlet water temperature of 25 °C. A step-by-step procedure was developed and validated to accurately simulate the heat process inside shell and tube gas coolers. This procedure also permits a direct and quantitative comparison between the different shell and tube heat exchangers.

2. Experimental facility

The R744 water-to-water tested heat pump has a nominal heating capacity of 5 kW at 0 °C evaporation temperature and 10 MPa gas cooler pressure (35 °C gas cooler outlet temperature). A patented control device of the back pressure unit and