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Economic analysis of the application of expanders in medium scale air-conditioners with conventional refrigerants, R1234yf and CO_2

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ABSTRACT

Expanders have been shown to improve the energy efficiencies of refrigeration systems. The current technology is also adequate to manufacture and integrate expanders to practical air-conditioners. In this paper, an economic analysis of the installation of expanders on to existing vapor compression cooling systems, particularly medium scale air-conditioners, is presented. Various refrigerants, including the established and the newly proposed varieties, are considered. From the investigations, it was found that when the expander efficiency is 50%, the payback periods of most conventional systems are below 3 years in high temperature countries with high electricity tariffs and are above 5 years in other countries. Expanders are especially attractive for the transcritical CO_2 and the R404A systems. The payback periods are shorter for systems with highly efficient expanders, high cooling loads, high ambient temperatures and for low refrigerating temperature applications.

Analyse économique de l'application des détendeurs dans les conditionneurs d'air de capacité moyenne utilisant les frigorigènes classiques, le R1234yf et le CO_2

Mots clés : détendeur ; conditionneur d'air ; efficacité énergétique ; économie ; frigorigène ; théorie

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Nomenclature

COP	Coefficient of Performance (–)
h	enthalpy (J kg^{-1})
m	mass (kg)
$\dot{m}$	mass flow rate (kg s^{-1})
P	power (W)
Q	heat rate (W)
μ	efficiency (-)

Subscripts

comp	compressor
evap	evaporator
expander	system with expander
exp_gain	gain due to expander
exp	expander
load	cooling load
valve	system with expansion valve

1. Introduction

At the 15th session of the Conference of Parties (COP 15) to the United Nations Framework Convention on Climate Change (UNFCC) in Copenhagen, Denmark, in 2009, climate change was underlined as one of the greatest challenges. Deep cuts in global emissions and low-emission development strategy were recognized as crucial to combat the issue (United Nations Framework Convention on Climate Change, 2009). These calls to curb greenhouse gases emissions are continuations of the 1997 Kyoto Protocol (United Nations Framework Convention on Climate Change, 1997) which calls for the reduction of the emissions of, among others, carbon dioxide and two groups of refrigerants, i.e. hydrofluorocarbons and perfluorocarbons. The production and emission of the more environmentally damaging substance, chlorofluorocarbons (CFCs), have been regulated even earlier, in 1987 under the Montreal Protocol (United Nations Environment Program, 1987). In response, more environment friendly refrigeration systems have been investigated in recent years. Two aspects are of particular concerns, namely the use of environmentally friendly refrigerants and the energy consumption issue.

With the phasing out of the use of CFCs, chemical substances like the hydrochlorofluorocarbons (HCFCs) and the hydrofluorocarbons (HFCs), were proposed and have been used as temporary alternatives. However, these compounds are considered to be greenhouse gases (Chen, 2008; Tsai, 2005a, b). As a response to these concerns, even more environmentally friendly refrigerants, mainly R1234yf (Honeywell,) and natural refrigerants (Hwang et al., 1998; Lorentzen, 1988, 1994, 1995; Lorentzen and Pettersen, 1993), particularly CO_2 and ammonia (NH_3) have been proposed as replacements.

As for the energy consumption issue, while it is actually a natural process, high energy consumption is damaging to the environment mainly because of our current over-dependence on energy produced by conventional fossil fuel burning processes which produce greenhouse gases (especially CO_2). The world energy consumption had grown steadily in the past decades. In 2010, the overall consumption grew by 5.5% (Enerdata,) while electricity consumption, which accounted for about 40% of the total energy consumption (U.S. Energy Information Administration, 2011), increased by 6.4% (Enerdata,). This growth was driven mainly by the growing demand of the developing countries, particularly China (the world's largest energy consumer in 2010) and India (the third largest, below the US). In Singapore, the electricity consumption increased by 9% in 2010 (AsiaOne,) with about 20% of the electricity consumed by households (Ministry of the Environment and Water Resources of the Republic of Singapore, 2008).

It is also reported that 40% of the world annual energy consumption was used for the provision of building-related facilities such as lighting, heating and air conditioning (Omer, 2008). In the UK, for example (Nicholls et al., 2009), in 2009, buildings were responsible for around 50% of all carbon emissions in the country. About half of the household electricity consumption in Singapore in 2009 was for air conditioning and refrigerators (AC&R) (Ministry of Trade and Industry of the Republic of Singapore (2007); Tay. In Guangzhou, China, AC&R contributed 30% of the total household electricity consumption in 2003 (Kondou et al., 2011). In the US, cooling and refrigeration contributed about 24% of the total electricity consumption of commercial buildings, while air conditioning consumed more than US$25 billion or about 20% of the total household electricity consumption in 2005 (U.S. Energy Information Administration, 2010). In the UK, the electricity consumption of AC&R applications contributed about 8% of the total greenhouse gases emissions in 2008 (Cowan et al., 2009). Globally, AC&R applications accounted for about 15% of the world electricity use (Coulomb, 2006). Most of the electrical energy used to operate AC&R systems is, and will still be for the foreseeable future, produced from fossil fuels which produce greenhouse gases, mainly CO_2. This accounts for about 80% of the total greenhouse gases emissions of AC&R while the rest is from the release of refrigerants into the atmosphere (International Institute of Refrigeration, 2004). It is therefore very important not only to have a refrigeration system using an environmentally friendly refrigerant, but also to have one with good energy efficiency.

Various methods have been proposed to improve the energy efficiency of refrigeration systems. One of the ways is to recover the power loss during expansion by replacing the conventional expansion valve with an expander (shown in Fig. 1), the idea that was initially proposed to increase the efficiency of the CO_2 refrigeration system (Lorentzen, 1994). When applied to conventional R22 and R134a systems, the coefficient of performance (COP) has been reported to increase by up to 15% (Robinson and Groll, 1998) and 12% (Goncalves and Parise, 2008), respectively. When applied to a transcritical CO_2 system, where the pressure difference between the suction and discharge lines is very high (in the range of 70 bar), the COP can increase by up to 50% (Fukuta et al., 2006).

An expander can be seen as a compressor operating in reverse. Therefore, any compressor mechanism can theoretically be used as an expander. These include the rolling piston (Hua et al., 2010; Li et al., 2009; Matsui et al., 2009,