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Energy Conversion and Management 48 (2007) 1150–1159
ENERGY CONVERSION & MANAGEMENT
www.elsevier.com/locate/enconman

Exergetic optimization of a key design parameter in heat pump systems with economizer coupled with scroll compressor

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Received 16 November 2005; received in revised form 15 August 2006; accepted 8 October 2006
Available online 28 November 2006

Abstract

The heat pump system with economizer coupled with scroll compressor can extend effectively its operating ranges and provide a technological method to enable the heat pump to run steadily and efficiently in severe weather conditions. The intermediate pressure, namely the working pressure of the refrigerant in the economizer, is an essential design parameter and affects crucially the performances of the heat pump system. According to the exergetic model setup for the heat pump system based on the second law of thermodynamics, the influences of the intermediate pressure on the performances are comprehensively analyzed using experimental data of the heat pump prototype. It is found that the optimal relative intermediate pressure (RIP) is between 1.1 and 1.3.

Keywords: Heat pump; Exergy analysis; Intermediate pressure; Scroll compressor

1. Introduction

As a double edge sword, social and economical development comes with not only civilization and prosperity but also environmental pollution and hazard for human beings themselves. In fact, it has become the most serious threat for human beings and wildlife alike. This effect is more vivid in the aspect of energy consumption, which brings about many environmental problems such as global climate change, global warming, ozone layer depletion acid rain, floating dust particulates in the atmosphere etc. These problems pose a serious threat to all forms of life on earth. In the 21st century, harmonious and sustainable development has become a necessity, and it is imperative to minimize the negative impacts of energy consumption on the environment and to develop clean and efficient energy technologies. Fuel burning is conventionally the main method for space heating in winter in cold regions such as northern China and the Yellow River basin. Space heating has become the top user of energy and source of pollutant emissions in these regions. Therefore, it has become essential to develop heating equipment with high efficiency and low emission. An electrically driven heat pump with high efficiency and convenience in use as well as being pollution free is an ideal and clean heating alternative.

However, a conventional air source heat pump cannot operate efficiently and steadily for long periods in cold regions where there is a large difference between the ambient and room temperatures borne by the heat pump. The problems that the heat pump has in operating in cold regions are low efficiency and such a great reduction in heating capacity that it cannot satisfy the heating requirement. Therefore, it is important to extend the operating conditions to relatively low ambient temperature, while maintaining, or even improving, the efficiency and reliability, and to minimize the reduction in heating capacity of the heat pump. To attain the above objective, many significant efforts and investigations have been made. Zogg and Ma showed that the key to efficient and steady operation of a heat pump under the conditions of large temperature dif-

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0196-8904/$ - see front matter
doi:10.1016/j.enconman.2006.10.007

Nomenclature

e_{xh}	specific exergy for flowing stream of matter (kJ/kg)
E_{xin}	rate of exergy input of system (kW)
E_{xout}	rate of exergy output of system (kW)
E_{xq}	rate of exergy flow associated with heating or cooling capacity y (kW)
E_{xq0}	rate of exergy flow associated with cooling capacity Q_0 (kW)
E_{xqk}	rate of exergy flow associated with heat transfer Q_k (kW)
E_{xw}	rate of exergy flow associated with electrical energy or mechanical energy (kW)
h	enthalpy (kJ/kg)
n	index of compression process (dimensionless)
P	electrical power of heat pump system (kW)
p	pressure (Pa)
p_c	discharge pressure (Pa)
p_e	suction pressure (Pa)
p_i	intermediate pressure (Pa)
Q	heating or cooling capacity (kW)
Q_0	cooling capacity of evaporator (kW)
Q_k	heat load of condenser (kW)
q_m	mass flow rate (kg/s)
q_{m0}	mass flow rate of refrigerant in evaporator (kg/s)
q_{mb}	mass flow rate of refrigerant in supplementary circuit (kg/s)
q_{mk}	mass flow rate of refrigerant in condenser (kg/s)
s	entropy (kJ/(kg K))
T	temperature of heating or cooling capacity (K)
t	temperature (°C)
T_0	ambient temperature (K)
T_d	discharge temperature (K)
T_e	evaporation temperature (K)
T_k	condensation temperature (K)
T_s	suction temperature (K)
W	electrical energy or mechanical energy (kW)

Greeks

Δe_{xh}	variation of specific exergy (kJ/kg)
ΔT	temperature difference (K)
ΔE_x	variation of rate of exergy flow (kW)
ΔE_{xde}	rate of exergy loss of system (kW)
η_{ex}	exergy efficiency (dimensionless)
λ_{ex}	exergy destruction coefficient (dimensionless)

Subscripts

0	ambient state
1	state 1
2	state 2
1–6	state points in Fig. 2
com	compressor
con	condenser
eco	economizer
eva	evaporator
exe	expansion valve A in supplementary circuit
exm	expansion valve B in main circuit
fd	filter–dryer

ferences is to improve the compression process, the only energy consuming process in the heat pump system. With the aid of comprehensive analysis and comparison among the various projects to optimize the compression process, they concluded that the heat pump system with economizer coupled with the scroll compressor is the only approach with broad applicability and commercial prospects [1,2]. Ma et al. have since developed a heat pump prototype with economizer coupled with a scroll compressor, and the performance characteristics of the prototype were experimentally investigated. The experimental results demonstrate that the prototype can realize a high temperature water supply and high capacity even under the low ambient temperature of −10 °C to −15 °C and can be used for winter heating in cold regions such as North China and the Yellow River basin [3,4]. Ma and Chai analyzed the thermodynamic cycle of the heat pump prototype and the influences of the main design parameters on the heat pump performances based on the first law of thermodynamics and the design parameters were optimized [5].

Exergetic analysis based on the second law of thermodynamics can be used to evaluate the distribution of energy losses from the viewpoint of energy quality so that measures and priorities with improvement potential can be developed. The refrigeration plant and heat pump system based on the reverse Rankine cycle have been exergetically analyzed for more than 10 years. An exergy analysis for a vapor compression refrigeration plant was conducted when its capacity is controlled by varying the compressor speed, and the performance and irreversibility of both the whole plant and its individual components was evaluated [6]. Kanoglu completed an exergy analysis of the multi-stage cascade refrigeration cycle used for natural gas liquefaction, and the equations of exergy destruction and exergy efficiency for the cycle and its main components and the expression for minimum work requirement for the liquefaction of natural gas were developed [7]. The irreversibilities in a one stage refrigeration process for a vapor compression cycle with R404A, R410A, R410B and R507 as working fluids was described, and the exergy losses and the influences of parameters on the losses were analyzed [8]. Bejan questioned the view that the degree of thermodynamic imperfection of the refrigeration and liquefaction plants that had been built did not depend on the refrigera-