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Research Paper

An optimal matching strategy for screw compressor for heat pump applications

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HIGHLIGHTS

- An optimal matching strategy for heat pump (HP) units applications was proposed.
- An index was introduced to represent the actual energy efficiency of the HP unit.
- The actual energy efficiency of the HP unit was improved significantly.

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ABSTRACT

An optimal matching strategy for screw compressor for heat pump (HP) applications was proposed in this study. The strategy focuses on the optimal matching between the built-in volume ratio (BVR) of screw compressors and the annual cooling and heating load demands. A performance index, the annual integrated coefficient of performance under actual operating conditions ($ACOP_A$), was introduced to represent the actual operational energy efficiency of the HP unit. The optimization mathematical model and generic framework of the optimal matching strategy were developed. The proposed strategy was applied to a ground-source HP unit to assess its performance. The results show that the optimal matching strategy improved the $ACOP_A$ by 6% at most, compared to the conventional matching method on BVR.

1. Introduction

Heat pump (HP) systems have been widely used in the HVAC field in recent years [1]. The HP unit is the main energy-consuming equipment of the entire HP system. However, a large amount of test data shows that the actual operational energy efficiency of the HP unit is only approximately 75% of its theoretical value [2–8], leading to a considerable increase in its actual operational energy consumption. Therefore, improving the actual operational energy efficiency of the HP unit is a key issue for HP applications.

The compressor is an important component of the HP unit, and its efficiency directly affects the energy efficiency of the unit [9,10]. Owing to the advantages of high efficiency, wide operating scope, and high reliability, screw compressors are widely employed in medium-capacity HP units. However, any mismatch between the internal and system pressure ratio will result in either under-compression or over-compression loss and lower efficiency [11]. In recent years, studies on the optimal matching of screw compressors mainly focus on how to match the built-in volume ratio (BVR) and the condition of the unit. Ma et al. [12,13] pointed out that the different BVRs of screw compressors should be considered to meet the different conditions of the HP unit in summer and winter. Although Ma et al. [13] advised to use a variable-volume-ratio compressor for HP applications, Refs. [14–16] showed that it is difficult to synchronously modulate the built-in pressure ratio under various operating conditions of the unit. Liu et al. [17] and Liu et al. [18] mainly carried out matching optimization studies on a fixed-volume-ratio screw compressor. Liu et al. [17] proposed an optimal compressor BVR for a screw chiller under standard conditions, and Liu et al. [18] carried out an experimental study on the optimal BVRs of a screw compressor under various standard conditions.

From the abovementioned studies, it was found that the existing methods for optimal matching on BVRs of screw compressors only consider the standard condition of the unit operating in a single season (i.e., summer or winter). Actually, the HP unit is mostly operating under non-standard conditions, and needs to meet the

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Nomenclature

ε	system operating pressure ratio, external pressure ratio
ε_i	built-in pressure ratio
V_i	built-in volume ratio (BVR) of screw compressor
$V_{i,f}$	built-in volume ratio (BVR) of screw compressor under full load condition
C_L	part-load rate (%)
PLF	part-load factor
Q_e	cooling load, total heat transfer rate of evaporator (kW)
Q_c	heating load, total heat transfer rate of condenser (kW)
$Q'_{e,max}$	maximum cooling capacity of HP unit (kW)
$Q'_{c,max}$	maximum heating capacity of HP unit (kW)
k	polytropic index
m_r	refrigerant mass flow rate (kg s^{-1})
V_{th}	theoretical volume displacement (m^3 s^{-1})
P	power (kW)
ω	specific power (kJ kg^{-1})
h	enthalpy (kg kJ^{-1})
p	pressure
K	overall heat transfer coefficient (W m^{-2} K^{-1})
α_r, α_w	refrigerant or water-inside average heat transfer coefficient (W m^{-2} K^{-1})
F	area (m^2)
t	temperature (°C)
Δt_m	mean temperature difference (°C)
M	water mass flow rate (kg s^{-1})
c_p	specific heat of water at constant pressure (kJ kg^{-1} K^{-1})
R_P	conductive resistance of tube material (m^2 K W^{-1})
R_f	fouling resistance on water side (m^2 K W^{-1})
D_{in}, D_{out}	inside tube diameter, outside tube diameter (m)
A_{in}, A_{out}	inside tube surface area, outside tube surface area (m^2)
EER	cooling energy efficiency
COP	heating energy efficiency
IPLV	integrated part-load value
NPLV	non-standard part-load value
ACOP	annual integrated coefficient of performance
η_{Vi}	built-in volumetric ratio efficiency
η_{com}	total efficiency of the compressor
η_m	motor efficiency
η_s	isentropic efficiency
η_n	internal leakage efficiency
η_υ	volume efficiency
G	mass velocity of water (kg s^{-1} m^{-2})
sh	superheating degree (°C)
sh_{ss}	static superheating degree (°C)
sc	subcooling degree (°C)
λ	thermal conductivity of water (W m^{-1} K^{-1})
μ	viscosity of water (kg s^{-1} m^{-1})
ρ	density (kg m^{-3})
γ	latent heat of vaporization of refrigerant (J kg^{-1})
λ_L	liquid refrigerant conductivity (W m^{-1} K^{-1})
μ_L	dynamic viscosity of liquid refrigerant (kg s^{-1} m^{-1})
ρ_L	saturated liquid density of refrigerant (kg m^{-3})
υ	specific volume (m^3 kg^{-1})

Subscripts

A	Actual operating condition
com	compressor
con, c	condenser
eva, e	evaporator
TEV	thermal expansion valve
r	refrigerant
w	water
1,2,3,4	refrigerant state point
i	inlet
o	outlet
υ	volume
s	isentropic
S	Summer
W	Winter
C	Cooling
H	Heating
f	full load

demands of both summer cooling and winter heating. However, for compressor manufacturers, it is difficult to obtain the building load demands characteristics. Conversely, for HVAC engineers, the compressor characteristics under variable operating conditions are generally unavailable. This technical barrier between the compressor field and HVAC field results in lower efficiencies of screw compressors in actual operation. In order to overcome this technical barrier, an optimal matching strategy between the BVR of screw compressors and the annual cooling and heating load demands is proposed in this study.

The aim of this study is to improve the actual integrated efficiency of compressors, and obtain an optimal annual integrated energy efficiency of the HP unit. In order to assess the effectiveness of the proposed strategy, it was applied to an optimization matching of a screw compressor for a specific ground-source HP unit.

2. Operating conditions of HP unit

2.1. External operating parameters

The external operating parameters of the water (ground) source HP unit mainly include the load-side water flow (WF), entering water temperature (EWT) and leaving water temperature (LWT), the heat source/sink-side WF, EWT and LWT. These parameters of the water (ground) source HP unit under standard conditions are listed in Table 1 [19].

As indicated in Table 1, the external operating parameters under cooling and heating conditions are different, and these parameters may vary with different applications of the HP unit. However, for a specific HP unit, the areas of the evaporator and condenser are constant under different operating conditions. Therefore, the system pressure ratio (ε) of the HP unit will be relatively different for different applications and sites, particularly between summer cooling and winter heating [20].

2.2. Part-load rate and part-load factor

The HP unit needs to meet the load demands of both summer cooling and winter heating. Owing to different climatic conditions and types of buildings, there are various annual load demands characteristics. Generally, there are three types: larger heating load, nearly equal cooling and heating loads, and larger cooling load. Because the HP unit capacity of a HP system is determined by the maximum value for both cooling and heating loads, the HP unit consequently operates in part-load most of the time.

In AHRI Standard 550/590, the part-load factor (*PLF*) of the HP unit is calculated based on the outdoor air temperature [21], and then it is used to obtain the integrated part-load value (IPLV) of the HP unit under the test cooling conditions. However, the