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Research Paper

Numerical research on coupling performance of inter-stage parameters for two-stage compression system with injection

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HIGHLIGHTS

- Dynamic coupling model of the two-stage compression system with injection was established.
- The formation process of the inter-stage parameters on the two-stage compression system with injection was analyzed.
- The characteristics of the two-stage compression process under different injection parameters was analyzed.
- The effect of the pulse number of the electronic expansion valve on the compression process was investigated.
- The dynamic response of inter-stage parameters was described when the injection parameters were changed.

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ABSTRACT

Aimed at a two-stage compression system composed of two rotary compressors, a simulation model of the two-stage compression system with injection was constructed and validated by experiments. Based on the simulation and experiments, the coupling relation among the injection parameters, the formation process of the inter-stage parameters and the effects of the inter-stage injection on the two-stage compression process were analyzed. The simulation results show that the mass flowrate and specific enthalpy of the injection refrigerant are a pair of coupling parameters which are constrained by the subcooler. The specific enthalpy of the injection refrigerant first increases and then decreases gradually as the mass flowrate of the injection refrigerant increases. The intermediate injection parameters have a great influence on the inter-stage parameters. The specific enthalpy of the injection refrigerant determines the direction of the change in the state point, and the mass flowrate of the injection refrigerant determines the degree of the change in the state point of the system. From the dynamic point of view, when the mass flowrate of the injection refrigerant increases, the intermediate mixing process is stabilized to a new "isobaric mixing" process after a transition from a stable "isobaric mixing" process to a variable "isocratic mixing" process.

1. Introduction

Air heat has been included in the renewable energy sector, and "coal-to-power" policy has been vigorously implemented in China, in order to reduce the proportion of fossil energy applications as well as the greenhouse gas emissions. Air-source heat pump is widely concerned with its high efficiency, energy saving and environmental protection [1]. However, when the air-source heat pump is operated at low temperature, there will be some problems such as the increase of the compression ratio, the increase of the exhaust temperature, the decrease of heating performance, etc. So, the domestic and foreign scholars put forward a variety of improvement measures [2–5]. Among them, the refrigerant injection technology can effectively solve the problem of adaptability of air source at low temperature [6–9], which has attracted much attention.

In recent years, the domestic and foreign scholars have made a lot of theoretical and experimental researches on the (quasi-) two-stage compression using injection technique. Wang et al. [10,11] built a scroll compressor performance test bench which could measure the internal pressure of the compressor, and carried out the experimental and simulant research on the intermediate injection process. It is proposed that the quasi-two-stage compression process is a time-varying process theory of adiabatic throttling + isobaric mixing. Heo et al. [12] proposed two novel inter-stage

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Nomenclature

A	area (m^2)
C_v	specific heat at constant volume ($kJ\ kg^{-1}\ K^{-1}$)
COP	coefficient of performance
D	equivalent diameter (m)
EEV	electronic expansion valve
h	specific enthalpy ($kJ\ kg^{-1}$)
H	height (m)
i	parameter for characterization of opening of exhaust valve of compressor
j	parameter for characterization of operational phase of compressor
L	length (m)
m	mass (kg)
$\dot{m}$	mass flowrate ($kg\ s^{-1}$)
m_{rat}	relative injection mass
N_{ps}	number of pulses in the electronic expansion valve (p)
p	pressure (MPa)
Q	heat rate (kJ)
Ref	refrigerant, R410A
S	state point
t	time (s)
T	temperature (°C)
v	specific volume
V	control volume (m^3)
W	compressor power (W)
x	two-phase fluid dryness

Greek symbols

α	compressor crank angle (rad)
β	chevron angle of plate heat exchanger
μ	dynamic viscosity ($kg\ s^{-1}\ m^{-1}$)
ρ	density ($kg\ m^{-3}$)

Subscripts

c	compression chamber
cf	first compression point in compression chamber of cylinder
con	condensation
cv	control volume
cyl	cylinder and liquid
eva	evaporation
ec	exhaust chamber
f	fluid state
g	gas state
h	heating
H	high-stage compressor
in	inlet
inj	injection
leak	leakage
L	low-stage compressor
m	intermediate
mix	mixing
out	outlet
ref	refrigerant
s	suction chamber
vc	exhaust valve closed
vo	exhaust valve opened

structural systems, which were compared with the traditional two-stage compression cycles. The results show that the average heating capacity of the new cycle has increased, but the average COP is almost the same. Mathison et al. [13] studied the number of scroll compressor injection ports on the performance of the system. It was pointed out that the three injection ports in the scroll compressor could improve the overall performance of the system by about 75% compared with the non-injection process. Yan et al. [14] designed a novel twin rotary variable speed compressor, with two symmetrical ejection ports on the baffle plate between the two cylinders. Under the condition of low temperature, the novel compressor could improve the heating capacity and COP by 5.6–14% and 3.5%. Wang et al. [15] proposed a rotary compressor with an injection structure on the slide plate, which could increase the amount of heating capacity and COP by 23.1–28.2% and 4.5–8.1%, respectively. The above studies on refrigerant injection technology have focused on quasi-two-stage compression systems consisting of one compressor. However, due to the limitations of the compressor structure, the problem that heating capacity can't satisfy the heating demand may arise during quasi-two-stage compression under extreme conditions. Two-stage compression system is more suitable for use in cold regions, relative to quasi-two-stage compression system [16]. Torrella et al. [17,18] analyzed the effects of refrigerant injection on the intermediate pressure and system performance using the thermodynamic cycle theory. It is indicated that the intermediate pressure, the compressor power and the system performance increase with the increase of the injection rate. Xu and Ma [19] pointed out that injection mass was the most important adjustment parameter in a two-stage compression system, and the volume ratio of high pressure cylinder to low pressure cylinder was also an important design parameter, because it had a great impact on the intermediate pressure and the injection mass. Jin et al. [9] established a dynamic compressor coupling model in a two-stage compression system with variable capacity, and analyzed the compression process of the two-stage compression system, the change of the intermediate pressure with time, the performance of the intermediate pressure changing condition and the influence of the intermediate pressure change on the system. But this did not take into account the influence of the intermediate injection process. Jiang et al. [20] established a general two-stage compression cycle with injection model by using the "input domain". The model can realize the comparison in performance among different levels of structural cycles, but it did not make a more in-depth study of the specific injection process. In conclusion, most of the existing researches on the two-stage compression system with injection are focused on the comparison among the different configurations and the optimization of the low- and high-stage cylinder volume ratio for the system. For the actual injection process, the impact of different injection parameters on the compression process remains to be further studied.

In view of the status of research on two-stage compression heat pump system, the two-stage compression cycle system with one-stage throttling and intermediate incomplete cooling with a subcooler consisting of two compressors (Referred to as "SC-IC", the system diagram and *p-h* diagram shown in Fig. 1) was selected as the research object in the present paper. Based on the continuity equation and the energy conservation equation, the simulation model of two-stage compression system with injection was established. And based on the simulant and experimental results, the coupling relationship between the injection parameters, such as the mass flowrate ($\dot{m}_{inj}$) and the specific enthalpy (h_{inj}) of the