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A control oriental model for combined compression-ejector refrigeration system

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ABSTRACT

Combined compression-ejector refrigeration systems have attracted lots of attention in recent years. In order to improve the running stability of the complex refrigeration system, it is necessary to obtain a simple and accuracy mathematical model for system control. In this paper, a control oriental model for combined compression ejector system is proposed. By analyzing the inner relationship between compressor and ejector, a hybrid model is built based on thermodynamic principles and lumped parameter method. Comparing with traditional theoretical models, the model is more suitable for system control due to its simpler structure and less parameters. Then the pressure pulsating phenomenon inside the piping system between compressor and ejector is investigated based on the model. The effectiveness of the proposed model is validated by experimental data. It is shown that the model can reflect the system performance under variable operating conditions.

1. Introduction

The ejector refrigeration technology is one of the active research areas in energy utilization for decades due to its usage of the low grade thermal energy such as solar energy, automobiles' waste heat and industrial exhaust heat [1,2]. However, there are two key factors that hold back the wide application of the ejector refrigeration technology [3]. One factor is the coefficient of performance (COP) of the ejector refrigeration system is still lower compared with the traditional compressor refrigeration system. And the other factor is that the system performance is greatly affected by the instability of the low grade thermal energy.

A great deal of research has been done to solve the above problems in recent years such as combined compression-ejector refrigeration system(CERS) [4], ejector-adsorption refrigeration system (EAdRS) [5], transcritical ejector refrigeration system(TERS) [6] and multi components ejector refrigeration system(MERS) [7,8]. CERS is a hybrid refrigeration system combined compressor and ejector which was proposed by Sokolov [9].

The use of a compressor changes the operating condition of the ejector, thereby the performance of CERS can be improved. Zhu [10] introduced a novel hybrid compression refrigeration system which could be improved by 9.1% comparing with the traditional compression refrigeration system. Xue [11] performed a dynamic model based on state space for CRES, the experimental data and simulation result both shown that the compressor operating condition has influence on the ejector performance. Wang [12] conducted an experimental study on a hybrid refrigeration system with R134a, the experimental result shown that there are optimal values for evaporator and generator pressure which could improve the COP by 34%. Zhao [13] analyzed the exergy destruction in a combined compressor ejector refrigeration system by building the thermodynamic model, results shown that about a half of the exergy destruction occurs in the ejector comparing with the whole refrigeration system.

CRES can overcome the effect of the instable low grade thermal energy with the help of the compressor driven by electronic power. Wang [14] carried out an investigation on the CRES driven by automobile exhaust waste heat, the result shown that the hybrid system can run steadily under variable operating conditions. Yan [15] performed an experimental study of a hybrid ejector compressor system with R134a. The experimental results shown that the performance of refrigeration system is improved by adjusting the EEV expansion based on compressor frequency.

CERS is more effective and stable compared with traditional ejector refrigeration system, however the complexity of the system also increases due to complex dynamic characteristics in the compressor. Especially the reciprocating compressor which is widely used in medium and small scale refrigeration system has complex

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Nomenclature

γ	specific heat ratio of gas	V	volume (m^3)
A	area (m^2)		
D	diameter (m)	*Subscripts*	
N	compressor motor speed (r/min)	e	evaporator
n	exponent of velocity distribution	g	generator
P	pressure (K Pa)	p	primary flow
R	radius (m)	s	suction flow
R_g	gas constant (J/(kg · K))		
T	temperature (K)		

thermodynamic behaviors because of its periodic working mode. Even though the ejector structure is very simple, the thermodynamic phenomenon inside ejector chamber is too complex to be expressed as a simple model. These factors increase the difficulty of system modeling and real time control.

Theoretical analysis based on conservation laws and auxiliary relationships is the main method in previous modeling processes [16]. Keenan and Newman [17] proposed a one-dimensional model to predict constant area ejector performance, the model is built on the basis of ideal gas dynamics, ignoring heat and friction losses and the conservation laws for mass, momentum and energy. Then Keenan [18] modified this model by introducing the concepts of constant pressure mixing and constant area mixing during mixing progress. Munday [19] developed the constant pressure model by introducing the concept of "hypothetical throat". The primary flow doesn't mix with the secondary flow until it reaches the "hypothetical throat" located downstream of the primary nozzle exit. Huang [20] presented a critical-mode model by assuming that the constant pressure mixing occurs in the constant area chamber. This model could explain the choking phenomenon of secondary fluid comparing with previous ejector models. Zhu [21] introduced the shock wave model by considering the nonuniform distribution of the secondary flow inside the mixing chamber. Calculation results shown that the shock wave model has a stronger ability to predict the ejector performance comparing with other 1D models. Cardemil [22] proposed a general model for the ejector used in the refrigeration system. Both dry and wet working fluids are considered based on the real gas equations.

The theoretical model can reflect the system thermodynamic performance accurately, however theoretical models contain many parameters which would need more time to be identified. And most theoretical models need a iterate solution procedure which are not suitable for the real time control of refrigeration system. In hybrid modeling progress, the complexity of theoretical model can be decreased by using parameter classification and identification. Zhu [23] proposed a hybrid model for ejector by simplifying the shock wave model. This model only contains two or three parameters and is much simpler comparing with traditional 1D ejector models. Ding [24] proposed a hybrid model for condenser in the ejector refrigeration system, nonlinear least squares method is used to identify parameters in this hybrid model. The experimental data shown that this model could predict the condenser performance accurately and the maximum error is less than $\pm 10\%$.

Although these hybrid models can be used to control the separate component successfully, the interaction between those components are not considering in the modeling process. Considering the complex thermodynamic phenomenon in the piping system between ejector and compressor, a simple model which can predict the relationship between ejector and compressor performance is a key factor in the control of CRES. Moreover, the pressure pulsating phenomenon in the reciprocating compressor piping system, which is neglected at most of previous work in the open literature during the modeling process [11,12], may influence the effectiveness of the control strategy and even lead to the change in operational mode of ejector. The prediction of the pressure pulsating phenomenon is necessary to obtain a better system control effect.

In this paper, a control oriented model for CRES is proposed. By combining the ejector model and compressor model, a uniform model is built to predict the ejector and compressor performance based on thermodynamic principles. Subsequently, the fundamental equations are simplified with the help of the lumped parameter method. The model is suitable for refrigeration system control due to only six parameters need to be determined. Considering the pressure pulsating phenomenon in the reciprocating compressor piping systems, the transient responses on the ejector suction pressure is analyzed based on the hybrid model.

2. Mathematical model

A combined compression-ejector refrigeration system is shown schematically in Fig. 1. The whole system mainly consists of a generator, an ejector, a condenser, an evaporator, a compressor, a pump and an electronic expansion valve (EEV). The system is very similar to the conventional ejector refrigeration system except that the steam flow through the evaporator is inhaled by a compression firstly. The steam is compressed by the compressor from P_e to P_s, and then, through the ejector, to pressure P_c. Thus, the ejector can have a higher suction pressure, which can lead to the improvement of ejector performance.

It should be noted that the pressure pulsating phenomenon is existed in the outlet of the reciprocating compressor due to the

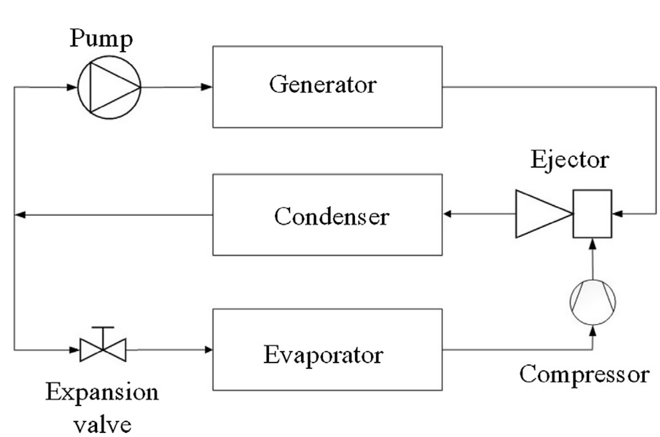

Fig. 1. Schematic diagram of the combined compression-ejector refrigeration system.