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A predictive model for the performance of the ejector in refrigeration system

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A R T I C L E I N F O

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A B S T R A C T

Ejectors are widely used in the refrigeration system and the evaluation of the ejector performance is important for the refrigeration system real time control. In this paper, a simple model is proposed to predict the performance of the ejector in the refrigeration system. A theoretical model is developed based on the thermodynamic principles and ideal gas property firstly. And then the proposed model is simplified to linear equations with four unknown parameters which can be determined by traditional identification methods easily. The accuracy of the model is validated by literature and experimental data. The results show that the model has a strong ability to predict the ejector entrainment ratio and critical back pressure. Furthermore, the proposed method is more accuracy and simpler than the previously published models. It is hoped that the proposed model is useful for the real time control of the ejector refrigeration system.

1. Introduction

Ejectors are widely used in the refrigeration system [1], vacuum equipment [2], fuel cell system [3] and desalination plant [4] due to its simple structure, long service life and low maintenance cost. The ejector refrigeration system has been a growing concern as its promising ability to use the low grade thermal energy such as solar energy in recent years. However, compared with the traditional vapor compression refrigeration system, the ejector refrigeration system not only has relative lower efficiency, but also presents a more complex thermodynamic behavior due to the supersonic flow phenomenon inside the ejector chamber. Furthermore, the instability characteristics of the low grade thermal energy also increases the difficulty of maintaining the optimum working conditions for the refrigeration system. It is a still challenging task to improve the efficiency and stability of the ejector refrigeration system.

Advanced control strategies provide a feasible way to solve the above problems. The control strategy based on the energy efficient optimization can improve the system performance while guarantee the stability of the system [5,6]. However, most of advanced strategies need a accurate mathematical model to predict the system performance. And the predictive model should be easy to calculate and implement considering the computing constrains of hardware and software used in the refrigeration system. As the ejector is a core component in the refrigeration system, a suitable model to predict the ejector performance is important in the system modeling and control process.

Several theoretical models have been developed to predict the ejector performance in recent years [7]. Keenan proposed the constant pressure mixing (CPM) model and constant area mixing (CAM) model to solve the problem of expressing the momentum conservation in the mixing process firstly [8]. And then Keenan pointed out that the ejector designed on CPM model has a better performance than the CAM ejector [9]. Munday and Bagster introduced the concept of the “hypothetical throat” [10]. It is assumed that the primary flow doesn’t mix with the secondary flow until it reaches the “hypothetical throat” where it is located downstream of the primary nozzle exit. Huang proposed a double choking mathematical model in order to explain the choking phenomenon of the primary and secondary flow [11]. The area ratio of the ejector can be determined based on the assumption that the hypothetical throat is located at the constant area chamber. Zhu described a shock wave model by considering the nonuniform distribution of the secondary flow in the suction chamber [12]. The predictive accuracy of the shock wave model is improved compared with the traditional 1D ejector model. Chen proposed a thermodynamic model to predict the ejector performance under critical mode and subcritical mode [13]. The experimental results from open literatures were used to validate the accuracy of the model and the comparing result shown that the proposed model has a strong ability to predict the performance of the ejector under overall modes. Mohammed developed a theoretical model to design the ejector used in the refrigeration system based on the real gas model [14]. The model provides a detailed method to determine all the ejector geometrical parameters unlike ejector design methods proposed before.

Even though many works have been done in the modeling of the

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Nomenclature

$\dot{m}$	mass flow ratio (kg/s)
γ	specific heat ratio of gas
ω	entrainment ratio
A	area (m^2)
D	diameter (m)
h	enthalpy (J/kg)
M	mach number
P	pressure (Pa)
R	gas constant (J/(kg·K))
T	temperature (K)
V	gas velocity (m/s)
v	sonic velocity (m/s)

Subscripts

c	critical back pressure
is	isentropic
p	primary flow
py	primary flow at 2–2 section
s	secondary flow
sy	secondary flow at 2–2 section
t	primary nozzle throat

ejector, the main purpose of most of ejector models is used to design and analysis the system instead of to control the system. Theoretical models have a strong ability to predict the performance of the ejector, however, iterative processes are applied to solve the couple equations which is introduced to express the complex thermodynamic phenomenon such as primary flow choking and shock waves. It will increase the computation time of system model and slow down the response speed of the system control strategy, even the total performance of the system will be deteriorated.

Meanwhile, ejector component efficiencies are introduced to explain the thermodynamic irreversible phenomenon during the fluid flow process [7]. It has been shown that the component efficiencies are dependant on the values of the ejector operating conditions and geometrical parameters [15,16]. Li studied the optimum problems of the ejector component efficiencies based on the sparsity enhanced optimization [17]. The accuracy of the model can be improved by optimize the values of component efficiencies. Both the ejector model and experimental results proposed by Huang [11] were used to validate the effectiveness of the proposed model. The maximum error for the prediction of the entrainment ratio reduces from 22.99% to 7.03%. Ma carried out the research on the change regulation of the hypothetical throat area ratio for the ejector used in the different refrigeration system [18]. The predictive error of the critical back pressure is less than 5% by determining empirical correlations from experimental results.

The accuracy of the model can be improved by identifying component efficiencies based on the experimental or simulation results. However, neither a uniform form of parameter expression nor a uniform identify method has been proposed still now. For example, the ejector model used in the state space of the vapor ejector refrigeration system [19] has five parameters to be identified while the model used by Yan [20] only have three parameters. The correction of the efficiencies in Wang [21] is quadratic equation while the one proposed by Cardemil [22] is only one order equation. It will undoubtedly increase the time consumption of parameter identification in the preliminary experiment.

Considering the requirement of real time implementation, a simple model to predict the ejector performance is proposed based on the basic thermodynamic laws and 1D analysis. Assuming that the value of component efficiency is constant for a fixed ejector in a special refrigeration system, the mathematical model can be simplified to two linear equations with four unknown parameters which can be identify by the traditional identification method easily. Open literature and experimental results are used to validate the accuracy of the proposed model. The result shows that the model has a strong ability to predict the ejector performance with different working fluids and operating conditions.

2. Ejector refrigeration system

A typical structure of the ejector refrigeration system powered by the low thermal energy are shown in Fig. 1. The refrigeration system consists of two subsystems: the low grade thermal energy collection subsystem and the ejector refrigeration subsystem.

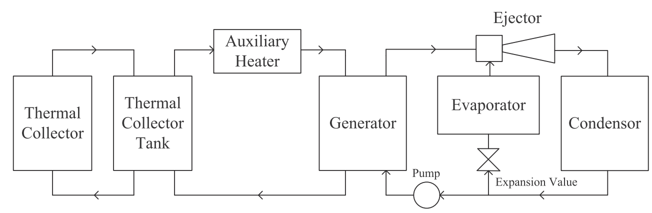

Fig. 1. Schematic diagram of the ejector refrigeration system.

The low grade thermal energy collection subsystem consists of a thermal collector, an energy storage tank and an auxiliary heater. The main purpose of the subsystem is to collect and transmit the energy to the ejector refrigeration system. Both the energy storage tank and auxiliary heater are used to maintain a steady energy supply considering the instability of the low grade thermal energy.

The ejector refrigeration subsystem is mainly made up of a generator, an evaporator, a condenser, an ejector, a pump and an expansion valve. The liquid refrigerant is evaporated by absorbing the thermal energy in the generator, and then the stream with high temperature and high pressure is delivered to an ejector. A low pressure region is generated in the ejector chamber and draws the vapor refrigerant with low pressure from the evaporator. In general the stream flows out from the generator is called “the primary flow” while the vapor comes from the evaporator is called “the secondary flow”. Both the primary and secondary flow is fully mixing in the ejector and flow into a condenser where it is condensed into a liquid. And then the refrigerant is divided into two stream, one stream is sucked into the generator by a pump, and the other stream flows through the expansion valve and vapors with a low pressure to generate the required refrigerating capacity in the evaporator. In this way, the cycle of the refrigerant in the ejector refrigeration subsystem is finished.

The performance of the refrigeration system can be evaluated by the coefficient of performance (COP), which is defined by the ratio between the refrigerating capacity and total energy. It has been shown that the performance of the ejector has a direct bearing on the value of COP [23]. The main performance criteria for the ejector is the entrainment ratio ω, which is given as

$$\omega = \frac{\dot{m}_s}{\dot{m}_p} \tag{1}$$

where $\dot{m}_p$ is the mass flow rate of the primary flow and $\dot{m}_s$ is the mass flow rate of the secondary flow. A accurate prediction of the ejector entrainment ratio is one of the key elements for the model based control strategy.

A typical ejector consists of a primary nozzle, a suction chamber, a mixing chamber and a diffuser, as shown in Fig. 2. The primary flow is accelerated to the supersonic speed across the primary nozzle and it’s