Korean J. Chem. Eng., **29**(4), 513-518 (2012)
DOI: 10.1007/s11814-011-0197-z

Exergy analysis of two-stage steam-water jet injector

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(*Received 29 October 2010 • accepted 1 August 2011*)

Abstract−Exergy analysis is used as a tool to evaluate exergy losses in the steam-water jet injector so as to improve its overall performance. What this article addresses here is mainly about a parametric study on the injector under various operating conditions, such as different inlet water temperature, inlet steam pressure, pressure ratio, entrainment ratio and flowrate ratio. In addition, the irreversible losses in the component parts of the two-stage injector were analyzed in detail. The results show that the operating parameters have great effects on exergy efficiency of the injector. The average exergy efficiency of the two-stage injector is 21% more than that of the single-stage one. Moreover, calculations based on experimental data indicate that the highest exergy losses due to irreversibility occur in the first-stage mixing chamber. In light of this comparison, the exergy losses occurring in the system are proportional to the exergy efficiency obtained by applying the system.

Key words: Exergy, Steam-water Jet Injector, Two-stage, Efficiency, Entrainment Ratio

INTRODUCTION

The steam-water jet injector is a simple and compact device without moving parts, which starts up easily within a few seconds, needs no external energy supply, and has a good heat transfer coefficient as large as 10^3 kW/m^2·K. Due to these advantages, the injector is applied in many areas of industry, such as thermal engineering, refrigeration and air conditioning, desalination, nuclear power plant, chemical industries, and so on [1]. In chemical engineering the steam-water jet injector is used as mixer, reactor or absorber [2].

The advantages of the injector attract many scholars to research on its working process and performance. Beithou obtained a mathematical model of the steam-driven jet pump under some assumptions for simplicity [3]. Balamurugan proposed correlations to estimate the fractional gas hold-up, mass transfer coefficient and interfacial area in the injectors [4]. The multiphase CFD modeling and the experiments were carried out to determine the hydrodynamic characteristics of the liquid-gas injectors [5]. Although much research on the injector has been carried out, most of it is focused on the performance of the single-stage injector, and a little attention has been paid to the two-stage one. The performance of the new two-stage injector-expansion transcritical CO_2 refrigeration cycle could be significantly improved [6]. A steam/steam injector cycle refrigerator was investigated to introduce a two-stage injector with annular primary at the second stage [7]. By the reviews it can be arrived at that the performance of the two-stage injector could be improved.

Energy and exergy methods are well-established methods used to investigate thermal processes. Considering the first law analysis of thermodynamics, the amount of energy consumed is calculated, disregarding the difference between work and heat. The thermal efficiency of the steam-water jet injector is nearly 100% because of its tiny radiating area. Therefore, the analysis of the steam-water jet injector based on only the first law is not adequate. In the exergy method, known as the second law analysis, the exergy loss caused by irreversibility, which is an important thermodynamic property in thermal process, can be calculated. If the exergy is calculated for a system instead of energy, the difference between energy qualities is also taken into account. Evaluating the systems in exergy basis is a much more suitable approach. Some researchers have expended considerable effort to analyze the performance of the injector by using the exergy method. Marian studied irreversible losses in the component parts of the injector by exergy analysis [8]. An exergy analysis is performed to guide the thermodynamic improvement for injector refrigeration cycle [9].

In this paper, exergy analysis was conducted to evaluate the performance of the injector. The research on a two-stage steam-water jet injector was carried out experimentally. We did a parametric study to determine how the injector performance varies with different operating parameters. The exergy efficiency of a two-stage injector was also compared with that of single-stage one. In addition, the irreversible losses in the component parts of the two-stage injector were analyzed.

EXPERIMENTAL

1. Experimental Apparatus

The two-stage steam-water jet injector mainly consists of a water nozzle, first-stage induced steam chamber, second-stage induced steam porous tubes, mixing tube, and diffuser, which is shown in Fig. 1. The steam-water jet injector is actually a type of direct contact heat exchanger, in which the steam is used as an energy source to heat the water. The traditional single-stage injector is taken as the first stage in the two-stage steam-water jet injector. The second-

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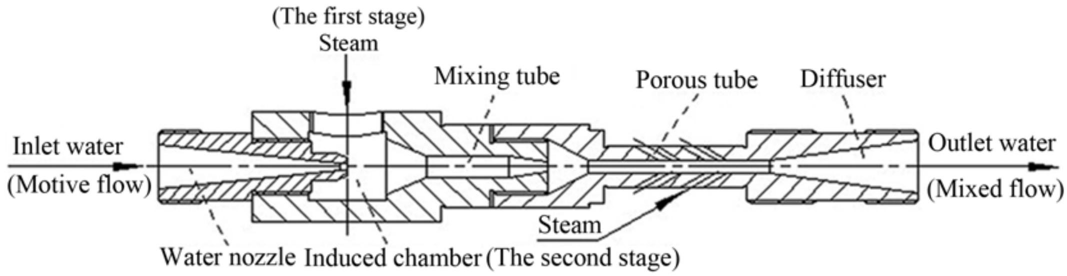

Fig. 1. Schematic diagram of two-stage steam-water jet injector.

stage steam is induced through the porous tubes in order to increase the outlet water temperature.

The operation of the steam-water jet injector is quite simple. The water nozzle is a convergent nozzle, since water is incompressible. The high pressure cold water accelerates through the water nozzle to create a very low pressure region at the nozzle exit. The steam is therefore induced into the mixing tube because of the pressure difference and shear stress at the steam-water interface, and then the transfer of energy and momentum takes place at the interface. The steam gradually condensates and the water temperature rises. At the same time the second-stage steam is induced to the mixing tube through the small porous tubes. The water temperature further rises. Through the diffuser, the velocity of the mixture gradually reduces and the pressure is recovered. Finally, high temperature water is obtained.

2. Experimental System

The experimental system of the two-stage steam-water jet injector is shown in Fig. 2, which mainly involves a steam-water jet injector, a water pump, two water tanks, the valves and the measuring devices. The steam is supplied by the steam boiler. It is possible to vary inlet water pressure, inlet water temperature, inlet steam pressure independently. The inlet water pressure and temperature are adjusted by water valves. The steam pressure and back pressure are adjusted by steam valve and back pressure valve, respectively. Temperatures and pressures are measured by K-type thermocouples (accuracy=1 K) and pressure gauge (accuracy=1% FS), respectively. The inlet water volumetric flux is measured by the rotameter, with the accuracy of 1.5% FS. The inlet steam mass flow is measured by vortex flowmeter, with the accuracy of 1% FS.

EXERGY ANALYSIS MODEL

The entrainment ratio ω can be used to describe working capability of the injector, which is the ratio between the ejecting fluid flux and the working fluid flux. It is defined as follows:

$$\omega = \frac{m_s}{m_w} \tag{1}$$

$$m_s = m_{s1} + m_{s2} \tag{2}$$

where m_s is the inlet steam mass flux and m_w is the inlet water mass flux.

Exergy efficiency is an important parameter which can reflect the energy utilization in quality. The exergy analysis model of the injector can be deduced in view of available energy point. The total exergy entering into the system can be calculated by

$$E_{in} = e_w m_w + e_s m_s \tag{3}$$

where e_w, e_s are inlet water exergy and inlet steam exergy.

According to Bejan et al. [10], the exergy can be seen in the following equation:

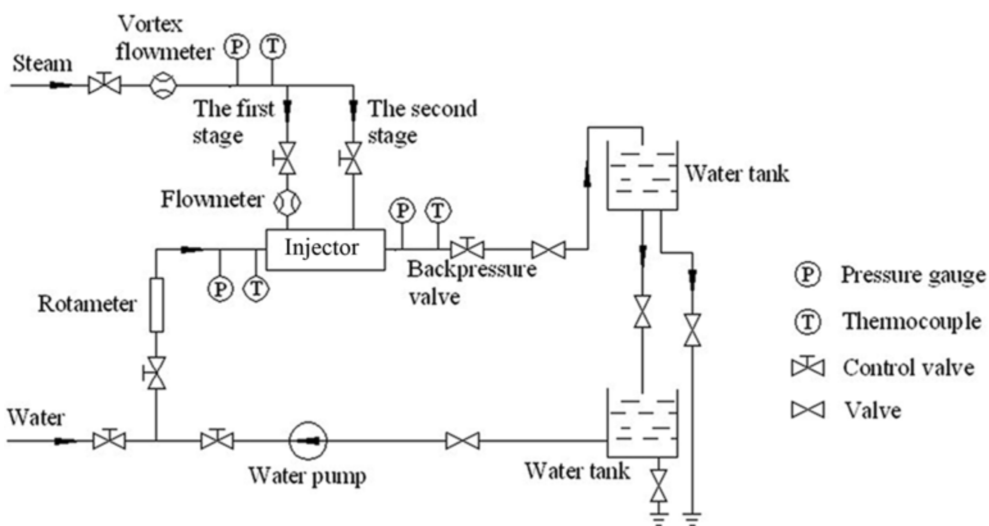

Fig. 2. Schematic diagram of experimental system.

$$e = h - T_e \cdot \Delta S + \frac{v^2}{2} \quad (4)$$

It is assumed that only physical exergy is used for injector flows. Chemical exergy of the substances is neglected. Kinetic and potential exergy of materials are ignored [6,9]. Thus the inlet water exergy and the inlet steam exergy are calculated by

$$e_w = h_w - h_e - T_e(S_w - S_e) \quad (5)$$

$$e_s = h_s - h_e - T_e(S_s - S_e) \quad (6)$$

where h_w, h_s are the enthalpies of inlet water and inlet steam; h_e is the enthalpy of the water at the environment temperature; S_w, S_s are the entropies of inlet water and inlet steam; S_e is the entropy of the water at the environment temperature.

The discharged exergy of the injector equals the exergy of outlet high temperature water, which is obtained by

$$E_{out} = m_c \cdot e_c \quad (7)$$

According to the theory of exergy analysis, the exergy of outlet high temperature water is calculated by

$$e_c = h_c - h_e - T_e(S_c - S_e) \quad (8)$$

where h_c is the enthalpy of outlet high temperature water.

The discharged water exergy of the injector is all effective. So the exergy efficiency of the system can be described as follows:

$$\eta = \frac{E_{out}}{E_{in}} = \frac{m_c \cdot e_c}{m_w e_w + m_s e_s} = \frac{(1+\omega) \cdot e_c}{e_w + \omega \cdot e_s} \quad (9)$$

The outlet parameters of the system are dependent on the inlet parameters once the structure of the injector is fixed. According to the mass conservation equation, the mass flux of the discharged water can be obtained by

$$m_c = m_w + m_s \quad (10)$$

When the heat loss is neglected, the energy conservation equation can be described by

$$m_w \cdot h_w + m_s \cdot h_s = m_c \cdot h_c \quad (11)$$

The pressure ratio ε is introduced, which is dependent on the inlet parameters and the structure of the injector. Then the discharged water pressure can be described as follows:

$$P_c = \varepsilon P_s \quad (12)$$

According to the state equation, the entropy of the discharged water can be described by the following expression:

$$S_c = f(h_c, P_c) \quad (13)$$

According to the analysis of the Eqs. (9)-(13), it is found that the exergy efficiency of the steam-water jet injector is correlated with the inlet water temperature T_w, inlet steam pressure P_s, pressure ratio ε and entrainment ratio ω.

In addition to the positive balance method described above, the exergy efficiency can be calculated by anti-balance method. In this paper the anti-balance method is used to verify the calculated results by the positive balance method. The whole irreversible loss in the flowing process can be obtained by

$$E_{losses} = E_{in} - E_{out} \quad (14)$$

Irreversible losses are generated in six different regions of the flow domain in the two-stage injector: in the water nozzle (WN), the first stage steam nozzle (SN1), the first stage mixing chamber (MC1), the second stage steam nozzle (SN2), the second stage mixing chamber (MC2) and diffuser (DF). Thus, the total losses E_{losses} can be written as a sum:

$$E_{losses} = E_{WN, losses} + E_{SN1, losses} + E_{MC1, losses} + E_{SN2, losses} + E_{MC2, losses} + E_{DF, losses} \quad (15)$$

If the performance of a two-stage injector is assessed, it is important to know exergy destruction in all of the above-mentioned regions. The exergy loss of each component $E_{i, losses}$ can be described by the following expression:

$$E_{i, losses} = m_i(e_{i, in} - e_{i, out}) \quad (16)$$

$$e_i = h_i - h_e - T_e(S_i - S_e) \quad (17)$$

From the perspective of the energy loss, the exergy efficiency of the system can be also described as follows:

$$\eta = 1 - \frac{E_{losses}}{E_{in}} \quad (18)$$

RESULTS AND DISCUSSION

In this part, the exergy efficiency of two-stage steam-water jet injector is studied experimentally under different inlet water pressure, inlet steam pressure and inlet water temperature by exergy analysis model. The operating parameters of two-stage steam-water jet injector are shown in Table 1.

Fig. 3 shows the exergy efficiency under different inlet water temperature. It is found that the exergy efficiency of the steam-water jet injector increases with the rise of inlet water temperature, with the average increase amplitude of 0.8%-1%/°C. When the inlet water temperature is 50 °C, the exergy efficiency of the two-stage injector can reach 59%, which is twice as much as the exergy efficiency under the inlet water temperature of 10 °C. The outlet water temperature increases with the rise of inlet water temperature. The increased amplitude of the outlet water temperature is almost equal to that of the inlet water temperature. So the values of the outlet exergy and the inlet exergy caused by temperature increase are almost equal under certain environmental conditions. According to Eq. (9), the exergy efficiency will increase if the numerator and the denom-

Table 1. Operating parameters of two-stage steam-water jet injector

Parameters	Values
Environment pressure P_e (MPa)	0.1
Environment temperature T_e (°C)	25
Inlet water temperature T_w (°C)	10-50
Inlet water pressure P_w (MPa)	0.35-0.6
Inlet steam pressure P_s (MPa)	0.15-0.5
Inlet water mass flux m_w ($kg \cdot h^{-1}$)	300-800
The ratio of the steam flowrate of the first stage to that of the second stage μ	3.3-10.7
Back pressure P_b (MPa)	0.1-0.45

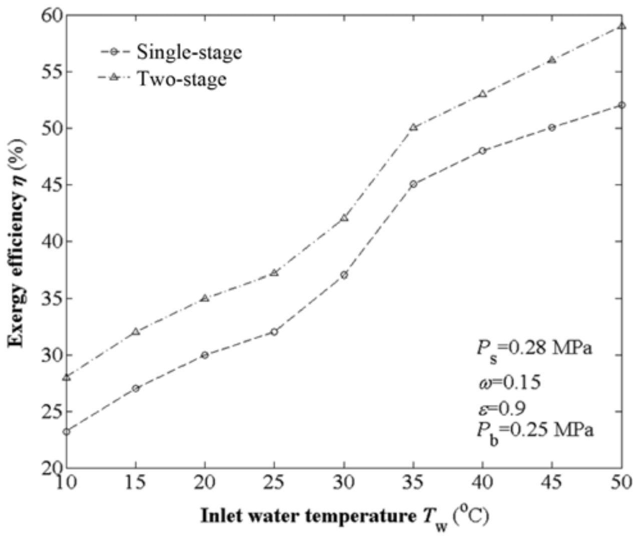

Fig. 3. Exergy efficiency under different inlet water temperature.

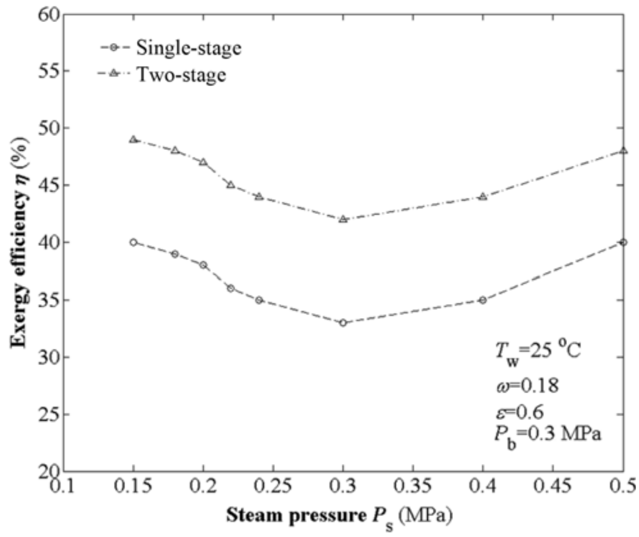

Fig. 5. Exergy efficiency under different steam pressure.

inator increase the same value. On the other hand, from the perspective of the energy loss, the average heat transfer temperature difference decreases when the inlet water temperature increases. The exergy efficiency increases because of the decrease of the irreversible loss.

Fig. 4 presents the relationship between the exergy efficiency and the entrainment ratio. As shown in Fig. 4, the exergy efficiency of the steam-water jet injector increases with the increase of entrainment ratio. When the entrainment ratio is 0.25, the exergy efficiency of two-stage injector is 51%. The reason is that the rise of the outlet water temperature is caused by the increase of entrainment ratio, which can enhance the heat transfer between the water and the steam. The discharged water exergy of the injector increases due to the increase of the outlet water temperature. As a result the exergy efficiency increases.

The exergy efficiency of the steam-water jet injector under different inlet steam pressure is shown in Fig. 5. It is found that the effect of inlet steam pressure on the exergy efficiency can be divided into two stages. At the first stage, the exergy efficiency decreases with the increase of inlet steam pressure. The exergy values of the steam and the outlet water increase at this stage, but the increase amplitude of the steam exergy is higher than that of the outlet water exergy [11]. This results in the decrease of the exergy efficiency. At the second stage, the exergy efficiency increases with the increase of inlet steam pressure. The increase amplitude of the outlet water exergy is higher than that of the steam exergy at this stage [11].

It can be seen from Fig. 5 that there exists a minimum in the effect of inlet steam pressure on the exergy efficiency. Therefore, the steam-water jet injector should be avoided operating at the steam pressure corresponding to the minimum exergy efficiency.

Fig. 6 gives the relationship between exergy efficiency of the steam-water jet injector and pressure ratio, which is nearly linear. The exergy efficiency increases with the increase of the pressure ratio. From the perspective of energy conversion, the enthalpy drop of the steam can be divided into two parts: One part is changed into the heat energy of the discharged hot water, and the other is changed into the

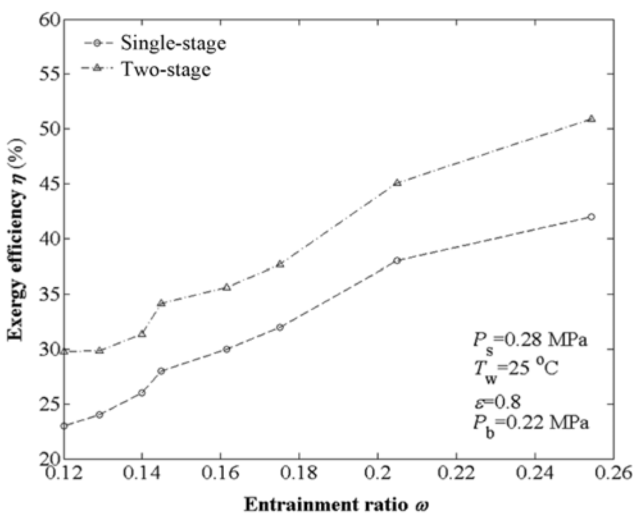

Fig. 4. Exergy efficiency under different entrainment ratio.

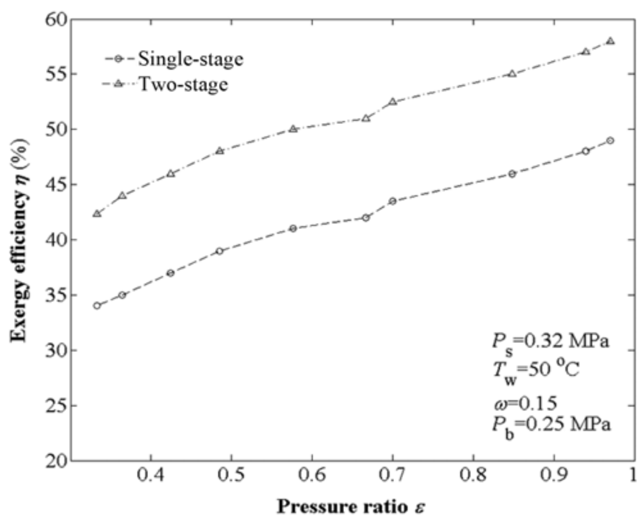

Fig. 6. Exergy efficiency under different pressure ratio.

pressure energy of the discharged hot water. The exergy of the pressure energy is much higher than that of the heat energy with the same amount [8]. It means that the pressure energy which is changed into by the enthalpy drop of the steam increases, and the heat energy decreases with the increase of the pressure ratio. This leads to the increase of the exergy efficiency. In the actual operation, therefore, the performance of the pressure increase should be applied sufficiently to obtain high economical efficiency [12].

It can be seen from Fig. 3-6 that the exergy efficiency of the two-stage injector is higher than that of the single-stage injector. The average exergy efficiency of the two-stage injector is 21% more than that of the single-stage injector. When the two-stage injector is adopted, the induced steam flux increases, while the inlet water flux almost keeps constant. Therefore, the outlet water exergy increases. Referring to Eq. (9), the increase of entrainment ratio and the outlet water exergy could result in the increase of the exergy efficiency. On the other hand, from the perspective of the energy loss, the steam and cold water can mix more fully in the two-stage injector. The exergy efficiency of the two-stage injector is higher due to more heat transfer.

The influence of the ratio of the steam flowrate of the first stage to that of the second stage on exergy efficiency of two-stage injector is shown in Fig. 7. It is obvious that exergy efficiency firstly decreases and then increases with the increase of the flowrate ratio. The steam flowrate of the first stage increases with the flowrate ratio. Although the heat transfer between the steam and water is enhanced, the increased amplitude of the steam exergy is higher than that of the outlet water exergy at the initial stage. This brings about the decrease of the exergy efficiency. When the flowrate ratio continues to increase, the increased amplitude of the outlet water exergy is higher than that of the steam exergy. It can be seen from Fig. 7 that there exists a minimum in the effect of the flowrate ratio on the exergy efficiency. Therefore, the two-stage injector should be avoided operating at the flowrate ratio corresponding to the minimum exergy efficiency.

The results of the calculation of the exergy losses in each component of two-stage injector are shown in Fig. 8(a) and Fig. 8(b).

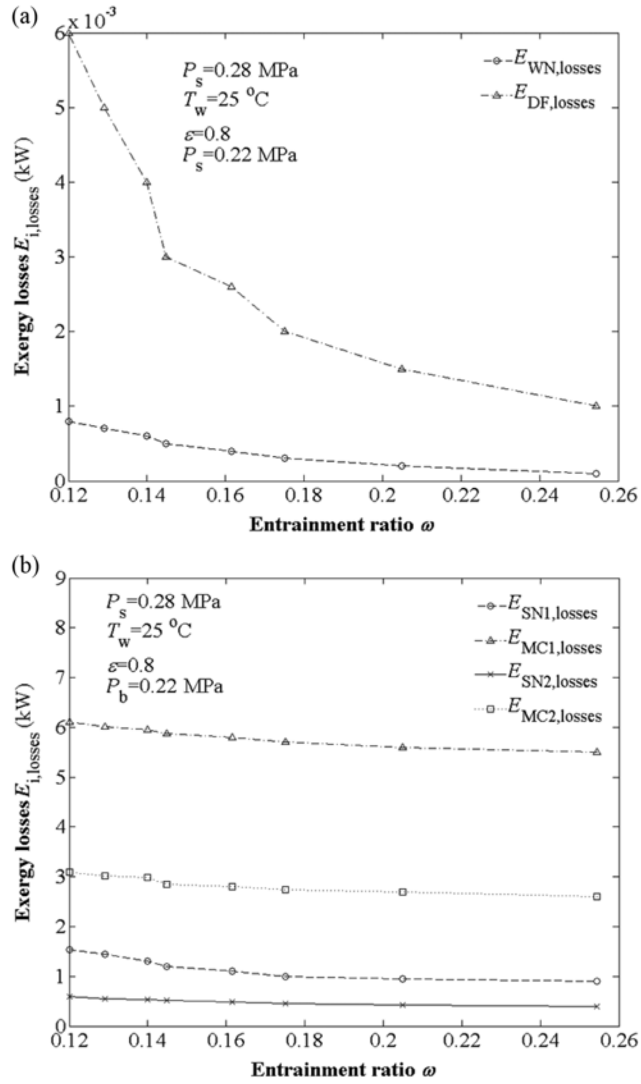

Fig. 8. (a), (b) Exergy losses in each component of two-stage injector under different entrainment ratio.

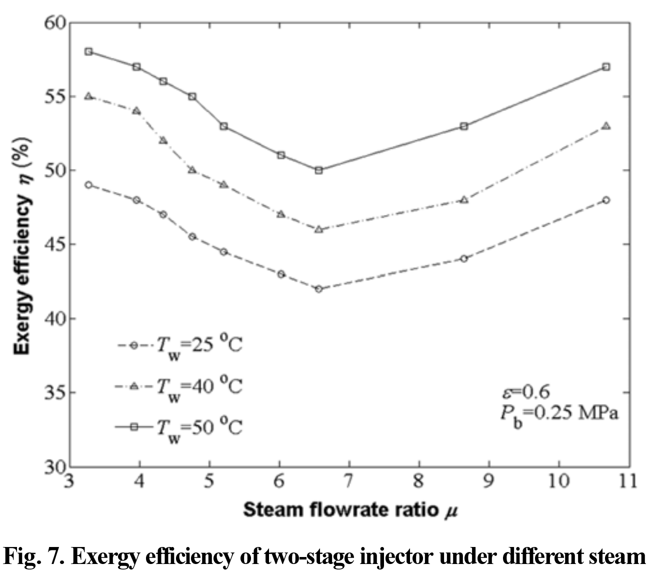

Fig. 7. Exergy efficiency of two-stage injector under different steam flowrate ratio.

The calculations were based on data collected during the experiment. The measured temperature, pressure and flowrate were used to calculate the exergy as well as the exergy losses in its component parts according to Eqs. (15)-(17). It is found that the exergy losses of each component decrease with the increase of entrainment ratio. The highest exergy losses due to the irreversibility occur in the first-stage mixing chamber. The exergy losses of the water nozzle are the lowest.

The inlet exergy and the outlet exergy of two-stage injector under different entrainment ratio are shown in Fig. 9. Total exergy losses calculated according to Eq. (15) are also shown in Fig. 9. With the increase of entrainment ratio, the inlet exergy and outlet exergy increase, and total exergy losses decrease. The exergy efficiency of two-stage injector was calculated according to Eq. (18). The results indicate that the exergy efficiency is the highest for high values of entrainment ratio, reaching 51% when entrainment ratio is 0.25. It can be seen from Fig. 9 that the results of exergy efficiency calculated by anti-balance method are consistent with that of exergy efficiency calculated by the positive balance method. By contrast, the exergy losses occurring in the system are proportional to the

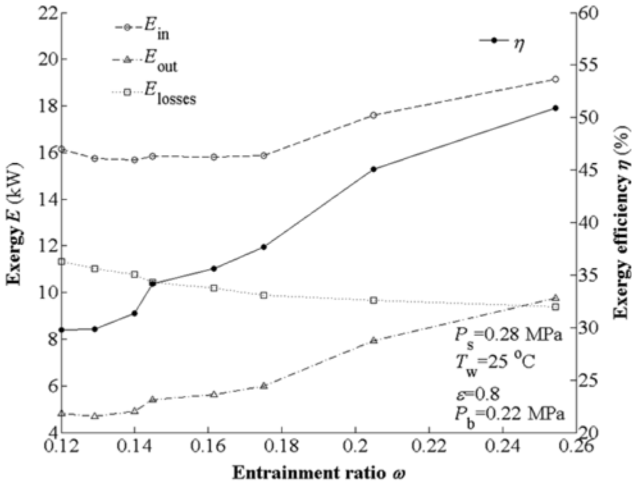

Fig. 9. Inlet exergy, outlet exergy, total exergy losses and exergy efficiency under different entrainment ratio.

exergy efficiency obtained by applying the system.

CONCLUSIONS

As shown above, an exergy analysis model of a two-stage steam-water jet injector was established. The variation of exergy efficiency, by means of the experiment, was compared in terms of different operating parameters. The irreversible losses in the component parts of the two-stage injector were analyzed, including water nozzle, the first stage steam nozzle, the first stage mixing chamber, the second stage steam nozzle, the second stage mixing chamber and diffuser. The results show that the exergy efficiency increases with the increase of inlet water temperature, entrainment ratio and pressure ratio. A minimum exergy efficiency occurs as inlet steam pressure changes. The increasing steam flowrate ratio makes exergy efficiency decrease at first and then increase. Results indicate clearly that the optimum exergy efficiency can be obtained through adopting the two-stage structure. The average increased amplitude of exergy efficiency is 21%. It is also found that the exergy losses of each component decrease with the increase of entrainment ratio. Through the exergy analysis above, it could be concluded that the amounts of exergy losses in the first-stage mixing chamber play a large and critical part in this process, while the exergy losses of the water nozzle are the lowest. In addition, the results of the exergy efficiency obtained by exergy losses method and the positive balance method are in good agreement. This study could provide a theoretical basis for the design and application of a two-stage steam-water jet injector.

ACKNOWLEDGEMENTS

This work was supported by the National Key Technology R&D Program of China (No. 2007BAB21B02) and Chongqing Science & Technology Commission (No. CSTC.2009AB3084).

NOMENCLATURE

A : area [m^2]
e : exergy [kJ/kg]
E : total exergy [kW]
h : enthalpy [kJ/kg]
m : mass flux [kg/s]
P : pressure [MPa]
S : entropy [kJ/(kg·K)]
T : temperature [°C]
v : velocity [m/s]

Greeks Symbols

ω : entrainment ratio
μ : the ratio of the steam flowrate of the first stage to that of the second stage
η : exergy efficiency
ε : pressure ratio

Subscripts

c : injector outlet
e : environment
i : each component
in : system inlet
out : system outlet
s : steam
w : water
DF : diffuser
MC : mixing chamber
SN : steam nozzle
WN : water nozzle
losses : exergy destruction
1 : the first stage
2 : the second stage

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