An Exploratory Study of the New Performance Index of the Heat Pump System Based on the Second Law of Thermodynamics

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Abstract: The coefficient of performance (COP) of the heat pump system, based on the first law of thermodynamics and reflecting the quantity relation of input and output energy, has certain limitations on the evaluation of energy-saving efficiency and the feasibility of the heat pump system. Based on the analysis of this problem and the second law of thermodynamics, a new performance index called the heating load of unit exergy loss is proposed, which reflects energy-saving efficiency and the feasibility of the heat pump system more scientifically and more objectively.

Key words: heat pump system, performance evaluation, coefficient of performance, heating load of unit exergy loss

1.INTRIDUCTION

Heat pump is a highly efficient energy-saving equipment.，through which usable mid-grade energy, several times higher than the high-grade energy, can be obtained by means of absorbing much low-grade heat from low-temperature heat source at the expense of COP is a traditional index of the heat pump's performance evaluation, which reflects the quantity ratio about the heat pump's heating load and the high-grade energy consumption. Clearly, COP only reflects the heat pump system's quantity relation of input and output energy, but neglects the quality of energy difference of them. Therefore, COP of the heat pump is just a performance evaluation index， which is based on the first law of thermodynamics. With this index, the performance quality of the same type of heat pumps can be evaluated directly. But as for the different types of heat pumps (such as the vapor compression heat pump and the absorption heat pump), their performance still can't be evaluated directly and reasonably by their COP, because their high-grade energy consumption is different in quantity and quality. In view of this, based on the principles of the second law of thermodynamics, this paper propose a new performance index, which reflects the relation of the quantity and quality of energy of the heat pump—the heating load of unit exergy loss.

2.THE ESTABLISHMENT OF THE INDEX OF THE HEATING LOAD OF UNIT EXERGY LOSS

2.1The Analyses of the Limitation of COP

The COP of heat pump indicates the ratio between the heating load of the heat pump and the high-grade energy consumption in quantity. Suppose the vapor compression heat pump and the absorption heat pump work under the same conditions (the temperature of high-temperature heat source is T_1, the temperature of low-temperature heat source is T_2), and both give the same heating load q_1 to the high-temperature heat source. The electric energy consumption of the vapor compression heat pump is w_0 ; the high-grade heat consumption of the absorption heat pump is q_0 (the temperature of the compensating heat source is T_0). Then,

The COP of the vapor compression heat pump can be indicated as follows:

$$\varepsilon_2 = \frac{q_1}{w_0} \qquad (1)$$

Where, ε_2 —The COP of the vapor compression heat pump.

And the COP of the absorption heat pump can be indicated as:

$$\varepsilon_2^{'} = \frac{q_1}{q_0} \qquad (2)$$

Where, $\varepsilon_2^{'}$ —The COP of the absorption heat pump.

In the same working conditions, the high-grade heat consumption of the absorption heat pump q_0 tends to be much more than the electric energy consumption of the electry-drived heat pump w_0 ,so the electry-drived heat pump's COP is far less than the absorption heat pump's (normally, the COP of the absorption heat pump $\varepsilon_2^{'}$ is 1.3 or so, and the COP of the electry-drived heat pump ε_2 is between 3 and 5). Therefore, it is difficult to determine which one of these two types of heat pump is more reasonable according to their COP. So COP has obvious limitations on the evaluation of the performance of different types.

2.2 The Heating Load of Unit Exergy Loss Of The Heat Pump

In recent years, exergy becomes a new parameter in thermodynamics and the energy field, which has been widely used to evaluate energy quality. The exergy is a generic terms of "the availability of energy", "available energy" and "efficient energy". It reveals the essence of the energy's degradation in all kinds of actual heating engineering in the view of "quantity" and "quality" of the energy. In all practical heating engineering, the quantity of energy remains constant, while the quality of energy is degraded. In this sense, we can say that energy-saving is actually "exergy-saving" or "reducing the exergy loss". Therefore, in this paper, an evaluation performance index of heat pump system called the heating load of unit exergy loss is proposed, which reflects the relation of the heating capacity and the exergy loss of the heat pump more scientifically and rationally.

The heating load of unit exergy loss can be expressed as the ratio of the heating load and the exergy loss of the heat pump. According to this definition, the exergy loss of heat pump should be determined first, which is the key to the heating load of unit exergy loss.

Based on the principles of the second law of thermodynamics, the exergy loss of the heat pump can be derived through the entropy analysis of the thermal process of the heat pump, and the entropy production can derive from its entropy function. In the following part, the method of determining the heating load of unit exergy loss of the vapor compression heat pump and the absorption heat pump will be discussed respectively.

2.2.1 The Heating Load of Unit Exergy Loss of The Electry-drived Heat Pump

（1）The analysis of the exergy loss of the electry-drived heat pump

The entropy function of the electry-drived heat pump system can be indicated as follows:

$$\Delta S_{sys} = S_f + S_g \qquad (3)$$

Where, ΔS_{sys} — The entropy variation of the electry-drived heat pump;

S_f — The entropy current of the electry-drived heat pump, positive to endothermic process, negative to exothermic process, zero to insulating process;

S_g — The entropy generation of the

electry-drived heat pump. irreversible process to positive, reversible process to zero;

The entropy current of the electry-drived heat pump S_f is composed of two parts: one is S_{f1}, which is produced during exothermic process of the heat pump to the high-temperature heat source T_1, and the other is S_{f2}, which produced during the endothermic process from the low-temperature heat source T_2.

Under the previous condition, the entropy current of the electry-drived heat pump during the exothermal process can be described as:

$$S_{f1} = -\frac{q_1}{T_1} \tag{4}$$

And the entropy current of the endothermic process can be expressed as:

$$S_{f2} = \frac{q_2}{T_2} = \frac{q_1 - w_0}{T_2} \tag{5}$$

Then, the total entropy current of the electry-drived heat pump can be indicated as:

$$S_f = S_{f1} + S_{f2} = -\frac{q_1}{T_1} + \frac{q_1 - w_0}{T_2} \tag{6}$$

To electry-drived heat pump, the entropy variation:

$$\Delta S_{sys} = 0 \tag{7}$$

Combining equations（6）,（7）and（3）, the entropy generation of the electry-drived heat pump can be worked out:

$$S_g = \Delta S_{sys} - S_f = \frac{q_1}{T_1} - \frac{q_1 - w_0}{T_2} \tag{8}$$

Thus, the exergy loss of the electry-drived heat pump can be got:

$$L = T_0 \cdot S_g = T_0 \cdot \left(\frac{q_1}{T_1} - \frac{q_1 - w_0}{T_2}\right) \tag{9}$$

Where, L —The exergy loss of the electry-drived heat pump;

T_0 —surrounding temperature.

（2）the heating load of unit exergy loss of the electry-drived heat pump

According to the above analysis, the exergy loss of unit heating load of the electry-drived heat pump can be expressed as:

$$R = \frac{q_1}{L} = \frac{q_1}{T_0 \cdot \left(\frac{q_1}{T_1} - \frac{q_1 - w_0}{T_2}\right)} \tag{10}$$

Where, R —The heating load of unit exergy loss of the electry-drived heat pump

2.2.2 The Heating Load of Unit Exergy Loss of The Absorption Heat Pump

（1）The analysis about the exergy loss of the absorption heat pump

The entropy function of the absorption heat pump can be indicated as:

$$\Delta S'_{sys} = S'_f + S'_g \tag{11}$$

Where, $\Delta S'_{sys}$ — The entropy variation of the absorption heat pump;

S'_f —The entropy current of the absorption heat pump, positive to endothermic process, negative to exothermic process, zero to insulating process;

S'_g — The entropy generation of the absorption heat pump, irreversible process to positive, reversible process to zero;

The entropy current of the absorption heat pump system S'_f is composed of three parts: S'_{f1}, which is produced during exothermic process to the high-temperature heat source T_1, and S'_{f2}, which is produced during endothermic process from the low-temperature heat source T_2, and S'_{f3}, which is produced during endothermic process from the compensation temperature heat source T_0.

With the previous assumption, the entropy current of the absorption heat pump system during the exothermal process to the high-temperature heat source, which is the same as the electry-drived heat pump, namely:

$$S'_{f1} = S_{f1} = -\frac{q_1}{T_1} \quad (12)$$

The entropy current of the absorption heat pump during the endothermic process from the low-temperature heat source can be described as:

$$S'_{f2} = \frac{q'_2}{T_2} = \frac{q_1 - q_0}{T_2} \quad (13)$$

The entropy current of the absorption heat pump system during the endothermic process from the compensation heat source can be expressed as:

$$S'_{f3} = \frac{q_0}{T_0} \quad (14)$$

Then, the total entropy current of the absorption heat pump system can be indicated as:

$$S'_{f} = S'_{f1} + S'_{f2} + S'_{f3} = -\frac{q_1}{T_1} + \frac{q_1 - q_0}{T_2} + \frac{q_0}{T_0} \quad (15)$$

To the absorption heat pump, its entropy variation:

$$\Delta S'_{sys} = 0 \quad (16)$$

Combining equations（15）,（16）and（11）, the entropy generation of the absorption heat pump can be worked out:

$$S'_{g} = \Delta S'_{sys} - S'_{f} = \frac{q_1}{T_1} - \frac{q_1 - q_0}{T_2} - \frac{q_0}{T_0} \quad (17)$$

Thus, the exergy loss of the absorption heat pump can be got:

$$L' = T_0 \cdot S'_g = T_0 \cdot \left(\frac{q_1}{T_1} - \frac{q_1 - q_0}{T_2} - \frac{q_0}{T_0}\right) \quad (18)$$

Where, L' —The exergy loss of the absorption heat pump;

T_0 —surrounding temperature.

According to the above analysis, the heating load of unit exergy loss of the absorption heat pump can be derived:

$$R' = \frac{q_1}{L'} = \frac{q_1}{T_0 \cdot \left(\frac{q_1}{T_1} - \frac{q_1 - q_0}{T_2} - \frac{q_0}{T_0}\right)} \quad (19)$$

Where, R —the heating load of unit exergy loss of the absorption heat pump

Similarly, the heating load of unit exergy loss of other types of heat pumps could be worked out with the above analytical methods.

According to the performance index — the heating load of unit exergy loss of heat pump, we could evaluate and compare not only the heat pump performance of same kinds visually, but also the heat pump performance of different types.

3.CONCLUSION

Taking the coefficient of performance (COP) of the heat pump system as an evaluation index of the heat pump performance, has certain limitations on comparing and evaluating the performance of different types of heat pumps. Based on the principles of the second law of thermodynamics, this paper proposes a new performance evaluation index of the heat pump—the exergy loss of the heat pump, and deduces the heating load of unit exergy loss of the electry-drived heat pump and the absorption heat pump separately. According to this new evaluation index of the heat pump performance, we could take all types of heat pumps’ performance for comparison and evaluation directly, and take a reasonable choice to the type of the heat pump.

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