The transfer law of exergy in the lines (pipes) and exergy loss analysis

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Abstract. In order to explore the transfer law of exergy in the lines (pipes), based on the generalized expression equation of exergy and the generalized exergy transfers and conversion equation, the transfer law of exergy in the lines (pipes) is derived, and then the exergy loss of three typical energies are analyzed based on the exergy loss model, which are electric exergy loss, pressure exergy loss and heat exergy loss. This paper reveals the change mechanism of exergy transfer process, which can provide more comprehensive guidance for energy saving.

1. Introduction

With the global energy shortage becoming more and more serious, distributed energy is introduced into the electric power system as an energy source, which can improve the flexibility of power supply [1-2]. After distributed energy is introduced into the power system, many distributed energy and power systems work together to form a huge integrated energy system (IES) [3], which brings greater challenges to the operation and management of energy [4]. Many scholars' researches on integrated energy system mainly focus on energy efficiency analysis [5], safety and stability analysis [6-7], coordinated optimal scheduling method [8-9], etc. Literature [10] reveals the essence and transmission law of energy in the lines (pipes), and establishes the energy network theory to conduct unified modeling and analysis of the integrated energy system. In literature [11], based on the energy network theory, the district electricity and heating system is analyzed, and the authenticity of the analysis results is verified through actual data. Literature [12] regards the electric network and the heating network as a whole, and proposes a method for solving the power flow of the electricity and heat networks. From the perspective of coordination and optimization, the literature [13] verifies the practicability and effectiveness of the optimization model of district electricity and heating system based on genetic algorithms. Literature [14] proposes a novel IES operation optimization method based on exergy economic analysis.

The above studies have played an important role in the application and promotion of distributed energy supply systems in the engineering field. However, most of the literatures only focus on the quantity of energy, and few on the quality of energy, which leads to the failure to fully reflect the value of energy. What’s more, there is few literatures to study the change mechanism of exergy transfer process, as a result, exergy change during transmission is not clear. The study of the transfer law of exergy has more theoretical and practical significance. In this paper, based on the generalized expression equation of exergy and the generalized exergy transfers and conversion equation, the transfer law of exergy in the lines (pipes) is derived and the exergy loss model is built. Combined with
the above theoretical analysis, the exergy loss analysis of three typical energies are analyzed. This article lays the theoretical foundation for the energy efficiency assessment based on exergy.

2. The transfer law of exergy in the lines (pipes)

The evaluation of energy includes the amount of energy and the quality of energy. Compared with the amount of energy, the quality of energy (i.e. exergy) or the level of energy can more deeply reflect the usable energy in the process of energy transfer and conversion. Therefore, it is necessary to conduct an in-depth discussion on the exergy transfer process.

The equation (1) is the generalized expression of exergy $P_x$, which is proposed in the literature [10].

$$P_x = (x - x_0) \varphi$$

Where, $x$ is the intensive property of exergy; $\varphi$ is the extension property of exergy; $x_0$ is the dead state value of the intensive property $x$.

![Figure 1. Cylindrical transfer line (pipe).](image)

Figure 1 shows the schematic diagram of the transfer process of exergy in the lines (pipes). $J$ is the flow density vector of the extension property $\varphi$, and the subscripts $A$ and $E$ respectively represent the head and end sections of the transmission line (pipe). The exergy loss during the exergy transfer from section $A$ to section $E$ is as shown in equation (2).

$$\Delta P_x = (x_A - x_0) \varphi_A - (x_E - x_0) \varphi_E$$

The dynamic equation of generalized exergy transfers and conversion is as shown in equation (3) [10].

$$\rho (x - x_0) \frac{d\varphi}{dt} = -\nabla \cdot [(x - x_0) J] + J \cdot \nabla x + (x - x_0) g_x$$

Where $\rho$ is the density of the transfer medium; $g_x$ is the source strength of the extensive property in unit volume transfer medium.

The left side of the equal sign in the equation (3) is the rate of exergy changing with time; the first term on the right side of the equal sign represents the exergy flowing in through the boundary of the unit volume transfer medium, and the second term represents the part of the mutual conversion with other forms of exergy driven by the intensity gradient, and the third term represents that the exergy of other forms is transformed into this form of exergy with the generation of the extensive property.

Analyze the integral volume of equation (3), and after simplification, the exergy balance equation in cylindrical transfer lines (pipes) can be obtained, which is shown in equation (4).

$$\frac{dP_x}{dt} = (x_A - x_0) \varphi_A - (x_E - x_0) \varphi_E + \int_{A}^{E} \varphi d\chi + \int_{A}^{E} (x - x_0) dx_g$$

Where $x_g$ is the function of the generation amount of extensive property in the cylindrical transfer lines (pipes) with respect to the length $L$.

This paper studies the change of exergy in steady state. In this case, the left and the right sides of equation (4) are equal to zero, and $d\varphi = dx_g$, so that the equation (4) can be simplified to equation (5).

$$\int_{A}^{E} (x_A - x_0) \varphi_A - (x_E - x_0) \varphi_E + \int_{A}^{E} \varphi d\chi + \int_{A}^{E} (x - x_0) d\varphi = 0$$

Equations (4) and (5) are the generalized exergy transfer equations in the lines (pipes), which are an important basis for studying the transfer law of the exergy in the lines (pipes). In the equation (5), the first two terms on the left side of the equal sign are the exergy loss caused by the flow in the cylindrical transfer lines (pipes), which can be shown as equation (6).
\[ \Delta x = (x_A - x_0) \varphi_A - (x_E - x_0) \varphi_E = \int_A^E \varphi d \chi - \int_A^E (\chi - x_0) d \varphi \]  

(6)

What’s more, energy loss caused by the flow in the cylindrical transfer lines (pipes) in steady state can be obtained from reference (11), which can be shown as equation (7).

\[ \Delta P = x_A \varphi_A - x_E \varphi_E = \int_A^E \varphi d \chi - \int_A^E x d \varphi \]  

(7)

Through equation (6) and equation (7), the relationship between exergy loss and energy loss can be obtained, as shown in equation (8).

\[ \Delta P_e = \Delta P + x_0 (\varphi_E - \varphi_A) = \Delta P + x_0 \Delta \varphi \]  

(8)

Equation (8) shows that compared with energy loss analysis in reference (16), exergy loss analysis takes into account the part of the energy that is lost due to irreversibility, and more profoundly reflects the essence of usable energy loss in the process of energy transfer. Equation (2) and equation (8) are equivalent, which also shows that the above derivation and analysis are correct. Equation (8) is the generalized expression of exergy loss in the lines (pipes) in steady state.

3. Exergy loss analysis

In this section, according to the above analysis, the exergy loss models of three typical energies will be established, which are electric exergy loss, pressure exergy loss and heat exergy loss. For electric energy, heat energy and pressure energy in steady laminar flow state, the generalized transfer equations in lines (pipes) have similar expressions, which is shown in equation (9) [11].

\[ \varphi_i = \frac{x_{iA} - x_{iE}}{R_i} \]  

(9)

Where, the subscript \(i\) represents the type of energy; In electric energy transfer, \(x\) is voltage and \(\varphi\) is current; in pressure energy transfer, \(x\) is pressure and \(\varphi\) is volume flow; in heat energy transfer, \(x\) is temperature and \(\varphi\) is heat flow.

(1) Electric exergy loss model in the lines

Electric energy is the highest level of energy, and the dead state value of the voltage \(x_0 = 0\). It can be seen from equation (8), the exergy loss generated in the process of electric power transmission is equal to the energy loss, which can be shown as equation (10).

\[ \Delta P_{xe} = \Delta P_e = \left( \frac{x_{eA} - x_{eE}}{R_e} \right)^2 \]  

(10)

Where, \(x_{eA}\) is the input voltage; \(x_{eE}\) is the output voltage; \(R_e\) is the resistance of the transfer line.

(2) Pressure exergy loss model in the pipes

The dead state value of the pressure \(x_0 \neq 0\), and the hot water in the pipe is incompressible, so, \(\Delta \varphi = 0\). Similarly, in the transmission process of hot water in the pipeline, the pressure exergy loss is equal to the pressure energy loss, which can be shown as equation (11).

\[ \Delta P_{xp} = \Delta P_p = \left( \frac{x_{pA} - x_{pE}}{R_p} \right)^2 \]  

(11)

Where, \(x_{pA}\) is the input pressure; \(x_{pE}\) is the output pressure; \(R_p\) is the flow resistance of the transfer line.

(3) Heat exergy loss model in the pipes

The loss caused by heat energy transmission in the pipeline includes two parts: the first part is the energy loss caused by heat flow in the process of transmission, which can be calculated by equation (9); in addition, the energy level will be reduced during the heat transfer, which will lead to the loss of the other part of heat energy. The total heat loss can be calculated by equation (12).
\[
\begin{align*}
\Delta P_{h1} &= \Delta P_{h2} + \Delta P_{h3} \\
\Delta P_{h4} &= \frac{X_{h\alpha} - X_{h\beta}}{R_h} \\
\Delta P_{h5} &= X_{h\beta}(\varphi_{h\alpha} - \varphi_{h\beta})
\end{align*}
\]  

(12)

Where, \(\Delta P_{h1}\) is the first part of the heat loss; \(\Delta P_{h2}\) is the second part of the heat loss; \(X_{h\alpha}\) is the input temperature of heat energy in the pipeline; \(X_{h\beta}\) is the ambient temperature; \(R_h\) is the total heat resistance of radial convection heat transfer; \(\varphi_{h\beta}\) is the output entropy flow; \(\varphi_{h\alpha}\) is the input entropy flow.

4. Conclusions

Different types of energy are not only different in quantity, but also in quality. The study of the transfer law of exergy has very important theoretical significance for improving energy efficiency. The theoretical derivation of the transfer law of exergy in the lines(pipes) is carried out based on the generalized expression equation of exergy and the generalized exergy transfers and conversion equation, and then the exergy loss model is built. The results show that compared with energy loss analysis, exergy loss analysis takes into account the part of the energy that is lost due to irreversibility, and more profoundly reflects the essence of usable energy loss in the process of energy transfer.

Nomenclature table

| Symbol | Description |
|--------|-------------|
| \(P_x\) | the generalized expression of exergy |
| \(\chi\) | the intensive property of exergy; |
| \(\rho\) | the extension property of exergy; |
| \(\rho_0\) | the dead state value of the intensive property \(\chi\). |
| \(\rho\) | the density of the transfer medium; |
| \(g_x\) | is the source strength of the extensive property in unit volume transfer medium. |
| \(g_x\) | is the function of the generation amount of extensive property in the cylindrical transfer lines (pipes) with respect to the length \(L\). |
| \(X_{h\alpha}\) | is the input voltage; |
| \(X_{h\beta}\) | is the output voltage; |
| \(R_h\) | is the resistance of the transfer line. |
| \(X_{pA}\) | is the input pressure; |
| \(X_{pE}\) | is the output pressure; |
| \(R_p\) | is the flow resistance of the transfer line. |
| \(\Delta P_{h1}\) | is the first part of the heat loss; |
| \(\Delta P_{h2}\) | is the second part of the heat loss.; |
| \(X_{h\alpha}\) | is the input temperature of heat energy in the pipeline; |
| \(X_{h\beta}\) | is the ambient temperature; |
| \(R_h\) | is the total heat resistance of radial convection heat transfer; |
| \(\varphi_{h\beta}\) | is the output entropy flow; |
| \(\varphi_{h\alpha}\) | is the input entropy flow. |
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