GRAPHIC PRESENTATION OF EXERGY LOSS IN MIXING ON AN ENERGY-UTILIZATION DIAGRAM

HONGGUANG JIN AND MASARU ISHIDA

Research Laboratory of Resources Utilization, Tokyo Institute of Technology,
Yokohama 227

Key Words: Energy, Exergy Loss, Mixing, Graphics, Energy Utilization Diagram, Power Generation System

In designing chemical or thermal process systems, mass and heat balances are considered. However, most designers have paid little attention to the exergy loss caused by mixing, because it is not calculated in the mass or heat balance. But the exergy loss in mixing sometimes plays a significant role, and one may expect an increase in efficiency or a decrease in utilities by reducing it.

In this paper, an advanced thermal power system is examined and a large exergy loss in mixing is observed in it. To show its importance, the amount is displayed graphically by decomposing an object process into individual subtarget processes.

1. Exergy Loss in Mixing in STIG

The STIG (Steam-injected gas turbine system)¹⁾ is an advanced thermal power systems because of its high performance at both full and partial load, its applicability in cogeneration, etc. The flow diagram is shown in Fig. 1. Air is compressed to 20 atm, the fuel is preheated to 400°C by the exhaust of the gas turbine, and steam at 500°C and 20 atm is generated in the HRSG (heat-recovery steam generator). These

three gas streams are fed to the combustor, where they are mixed and the combustion reaction proceeds.

Figure 2 shows the exergy loss caused by the combustion reaction with mixing of the three inlet streams. The total exergy loss is divided into three parts: losses caused by preheating (I_a , I_b , I_c), mixing (II) and chemical reaction (III). It is known that the exergy loss for the combustion reaction is very large. But Fig. 2 shows that the exergy loss for mixing is significantly large, too.

We have developed a method to display the exergy loss on the EUD (energy-utilization diagram).²⁾ So

Fig. 1. Process flow diagram for STIG

* Received June 4, 1992. Correspondence concerning this article should be addressed to M. Ishida.

Fig. 2. EUD for combustion reaction with mixing

far, however, the mixing exergy loss in a chemical reactor has been neglected because it has not been considered to be so important. But Fig. 2 indicates that it cannot be neglected.

2. Presentation of Exergy Loss of Mixing on EUDs

2.1 Decomposition of exergy loss in combustor

To tackle the problem of such a process, the object process is decomposed into subtarget processes, as shown in Fig. 3. Then, the total exergy loss caused by the target process is composed of those in preheating, mixing and reaction. The first step is to preheat each inlet stream to the temperature of reaction, where the outlet composition and pressure are the same as those at the inlet and it is assumed that only heat exchange occurs. The second step is to mix the streams, where only outlet composition is changed. The final step is to make the reaction proceed.

2.2 Automatic drawing of mixing process on EUD

The above procedure was applied to the combustion reaction in the STIG. The conditions of temperature, pressure and the molar flow rate of each component are summarized in Table 1. Based on these streams, the EUD for the reaction subsystem with multi-stream mixing is shown in Fig. 2.

The preheating of the three inlet streams is represented in I_a , I_b and I_c . Since the abscissa and the ordinate respectively denote the amount of energy exchanged and the energy level, the lines of A_{ea} for I_a , I_b and I_c show an increase in energy level by accepting energy. For such thermal processes, the energy level A is given by

$$A = 1 - T_o/T \quad (1)$$

where T_o is the environmental temperature ($= 298.15 \text{ K}$). This heat is supplied from the reaction environment at 1200°C ($A_T = 1 - 298.15/1473.15 = 0.798$).

For ideal gases, the mixing of the three input streams yields an entropy increase, ΔS :

$$\Delta S = R \sum_{i=1}^3 F_i \ln y_i$$

Fig. 3. Decomposition of an object process for drawing EUD

Table 1. Stream data with flow rates in mol/mol-CH₄

Stream		O ₂	N ₂	CO ₂	H ₂ O	CH ₄	T [°C]	P [atm]
F _{in1}	air	4.64	17.3		0.31		507	20
F _{in2}	fuel					1.0	400	20
F _{in3}	steam				7.35		500	20
F _{out}	flue gas	2.64	17.3	1.0	9.66		1200	20

where F_i and y_i respectively are molar flow rate and mole fraction of component i . Multiplying the above value by the environmental temperature T_o , we can calculate the exergy loss, which is represented as II in Fig. 2. In this case, the rectangular area II indicates the exergy loss by mixing. But since the height of the rectangle is unity, the width of the rectangle shows the exergy loss, too. Hence the exergy loss for mixing can be found by the scale of the abscissa of Fig. 2, since both exergy loss and energy have the same unit. But the abscissa of area II is not related to the amount of energy transformed, because ΔH for mixing is zero.

Finally, the combustion reaction takes place at a constant temperature, 1200°C . The energy level of a reaction can be calculated as

$$A_r = 1 - (T_o \Delta S_r / \Delta H_r) \quad (2)$$

This is the energy level for the theoretical equilibrium temperature. At equilibrium, we have

$$\Delta G_r = \Delta H_r - T_{r,eq} \Delta S_r = 0 \quad (3)$$

When Eq. (3) is substituted to (2), we have

$$A_r = 1 - (T_o / T_{r,eq}) \quad (4)$$

The value of A_{ed} for III in Fig. 2 is calculated by Eq. (2) (or Eq. (4)) and the line shows the energy donated by combustion by its width and the energy level by its height. Since the donated energy becomes heat at 1200°C , i.e., $A_T = 0.798$, the shaded area III shows the exergy loss by chemical reaction.

By representing the exergy loss of each phenomenon, the exergy loss in mixing in the STIG is found

to be very large, amounting to 49.3 kJ/mol-CH₄. It cannot be neglected as compared to the exergy loss in preheating I and reaction III, 223 kJ/mol-CH₄. The STIG has an efficiency as high as 48.2% as the ratio of electricity generated to the combustion heat of methane. But if the exergy loss 49.3 kJ/mol-CH₄ could be diminished to zero, its efficiency would increase to 54.4%. In a conventional thermal system without steam injection the exergy loss caused by mixing of fuel and air is about 12 kJ/mol-CH₄. Hence the mixing exergy loss in STIG is significantly large. Since the calculation of exergy loss can be made on the basis of thermodynamic data of the input and output streams, EUD in Fig. 2 can be drawn automatically. Consideration of exergy loss in mixing may become a key factor in the design of new thermal and chemical

process systems.

Conclusion

Mixing exergy loss can be drawn automatically on EUDs by decomposing an object process into subtarget processes, and it is effectively applied to the combustion reaction with mixing of steam. This makes graphic exergy analysis more powerful and provides guidance in improving recently advanced thermal power systems.

Literature Cited

- 1) Cheng, D. Y.: US Patent No. 4,128,994, Dec. 12 (1978).
- 2) Zheng, D., Y. Uchiyama and M. Ishida: *Energy*, **11**, 631 (1986).