

Optimization proposal of waste heat recovery exchanger by net present value method

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Keywords: Net present value (*NPV*), Number of heat transfer unit (*NTU*), Heat recovery exchanger.
Abstract. In this paper, the optimization proposal of a waste heat recovery exchanger has been studied by the method of net present value (*NPV*). The result shows that the maximum income and recover maximum heat can be obtained as the optimal *NTU*=2.19.

Introduction

With the rapid development of society, reducing energy consumption and recovering waste heat become the focus of study. In the past, many scholars have given various objects for optimizing the heat recovery to get more heat [1]. As an economic mean, the net present value (*NPV*) has been employed to analyze the profitability of a project investment. For example, the carbon capture and storage facility can be determined by *NPV* method [2]. The post-combustion carbon capture processes were optimized by *NPV* [3]. In addition, Mokhtar et al. has utilized *NPV* to evaluate the system when they explore solar thermal system designs with fixed operations [4]. Soshinskaya et al. has evaluated the renewable micro-grid for Dutch water treatment plant by *NPV* [5].

In this paper, the *NPV* method will be used to explore the economy of the heat recovery exchanger of the boiler which consumes dimethyl ether (DME) as fuel. Because, DME is a new clear energy with high combustion efficiency, lower CO₂ and NO_x emission, furthermore its smoke has no SO₂ [6].

Theoretical Analysis

Here, the consumption of DME for the industrial boiler is 100kg/h. The correlation parameters which are used to design the air exchanger heat are given in Table 1.

Table 1. Correlation parameters in air heat exchanger design [7].

Title	Symbol	Value	Title	Symbol	Value
Mass flow rate of smoke, kg/h	qm_1	1076.7	Mass flow rate of air, kg/h	qm_2	976.7
Specific heat of smoke, kJ/kg·K	Cp_1	1.117	Specific heat of air, kJ/kg·K	Cp_2	1.009
Inlet temperature of smoke, °C	T_1	250	Inlet temperature of air, °C	t_1	20
Adiabatic index of smoke	k_1	1.3	Adiabatic index of air	k_2	1.4
Influence coefficient of smoke	F_1	0.0025	Influence coefficient of air	F_2	0.01
Heat effective coefficient	ψ	0.7	Ambient temperature, °C	T_0	20
Price of waste heat, Yuan/GJ	CQ	25	Heat transfer coefficient, W/(m ² ·K)	K	13

The exergy method is used to analyze the energy in exchanger. Both the smoke and air are assumed as ideal gas with constant physical property. The flow resistance loss and heat loss will be considered. The expressions of *NTU* and dimensionless quantity *R* are [8]:

$$NTU = \frac{t_2 - t_1}{\Delta t_m} = \frac{KA}{q_{m2}C_{p2}} \quad (1)$$

$$R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{q_{m2}C_{p2}}{q_{m1}C_{p1}} \quad (2)$$

In which, A is heat transfer area, m^2 ; T_1, T_2, t_1, t_2 are the inlet and outlet temperatures of smoke and air, K ; Δt_m is the logarithmic mean temperature difference, whose expression is:

$$\Delta t_m = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \left(\frac{T_1 - t_2}{T_2 - t_1} \right)} \quad (3)$$

When ignoring the heat loss, the calculation formulas in heat balance and heat transfer are:

$$Q = q_{m1}C_{p1}(T_1 - T_2) = q_{m2}C_{p2}(t_2 - t_1) \quad (4)$$

$$Q = KA\Delta t_m \quad (5)$$

Simplifying above equations and consider the heat loss, we can get the air preheating temperature:

$$t_2 = \psi (t_2' - t_1) + t_1 = \psi \left(\frac{[e^{NTU(R-1)} - 1] \cdot T_1 + (R-1) \cdot e^{NTU(R-1)} \cdot t_1}{R \cdot e^{NTU(R-1)} - 1} - t_1 \right) + t_1$$

(6)

The heat exergy can be got by air in the heat exchanger [1]:

$$\Delta E_c = Q - T_0 \Delta S = q_{m2}C_{p2}[(t_2 - t_1) - T_0 \ln \frac{t_2}{t_1}] \quad (7)$$

The flow exergy loss of smoke and air are:

$$\Delta E_{r1} = \frac{k_1 - 1}{k_1} q_{m1}C_{p1}T_0 \ln(1 - F_1NTU) \quad (8)$$

$$\Delta E_{r2} = \frac{k_2 - 1}{k_2} q_{m2}C_{p2}T_0 \ln(1 - F_2NTU) \quad (9)$$

The value of heat exergy get by air every year is expressed as follow:

$$I_c = C_e \tau \Delta E_c \quad (10)$$

In which, the relation of exergy price (C_e) and heat waste price (C_Q) is $C_e = (\sigma - 1)C_Q / (\sigma - 1 - \ln \sigma)$ [9]; $\sigma = T_1/T_0$ is the inlet temperature factor in heat exchanger; τ is working time and $\tau = 6000h$.

The operating cost of exchanger is the cost of exergy loss, which is made up for nonequivalent mechanical energy [1]. Therefore, we introduce the convert coefficient $n=3$ in this paper [10]. The operating cost per year of waste heat recovery exchanger is:

$$I_r = -nC_e \tau (\Delta E_{r1} + \Delta E_{r2}) \quad (11)$$

There are 2 parts of initial investment, one is the fee of $I_0=5000$ Yuan with no relation with heat exchange area, namely components like hang and support; another is the expense related to the area, like the materials expenses. The price of Q235-A tube is $Y_1=1.4 \times 10^4$ Yuan/t, the price of box is $Y_2=1.0 \times 10^4$ Yuan and the density is $\rho=7.85 \times 10^3$ kg/m³, pipe size is $\Phi 52 \times 2$ mm, the ratio about the weight of box and element is 0.45, the investment per heat exchange area is $I_A = (Y_1 + 0.45Y_2) \cdot \delta \cdot \rho = 290.45$ Yuan/m². The initial investment and net income of the heat exchanger can be expressed by:

$$I = I_0 + I_A \cdot A \quad (12)$$

$$I_N = I_c - I_r = C_e \tau [\Delta E_c + n (\Delta E_{r1} + \Delta E_{r2})] \quad (13)$$

According to the relevant economics theory, the calculation formula of the heat exchanger is:

$$NPV = \sum_{t=1}^T I_N (1+i_c)^{-t} - I = I_N \sum_{t=1}^T (1+i_c)^{-t} - I_0 - I_A \cdot A \quad (14)$$

In which, i_c is the benchmark yield and $i_c=0.15$; T is the operation life and $T=15$ years.

Calculation and Analysis

According to the present equations, many important parameters like air preheating temperature are connected with NTU . With different NTU , air preheating temperature (t_2), the value of the heat exergy get by air (I_c), the operating cost per year (I_r), net income (I_N) and NPV are given in Table 2.

Table 2. The value of t_2 , I_c , I_r , I_N and NPV when NTU take different values.

NTU	t_2/\square	$I_c/\text{Yuan}\cdot\text{year}^{-1}$	$I_r/\text{Yuan}\cdot\text{year}^{-1}$	$I_N/\text{Yuan}\cdot\text{year}^{-1}$	NPV/Yuan
1	104.18	5748.66	1774.51	3974.14	17122.13
2	133.77	9959.41	3564.37	6395.04	25161.85
3	148.68	12421.93	5369.87	7052.06	22887.59
4	157.55	13985.66	7191.32	6794.34	15264.43
5	163.35	15046.74	9029.05	6017.69	4606.93
6	167.39	15801.95	10883.38	4918.57	-7936.19
7	170.31	16358.48	12754.65	3606.829	-21740.11

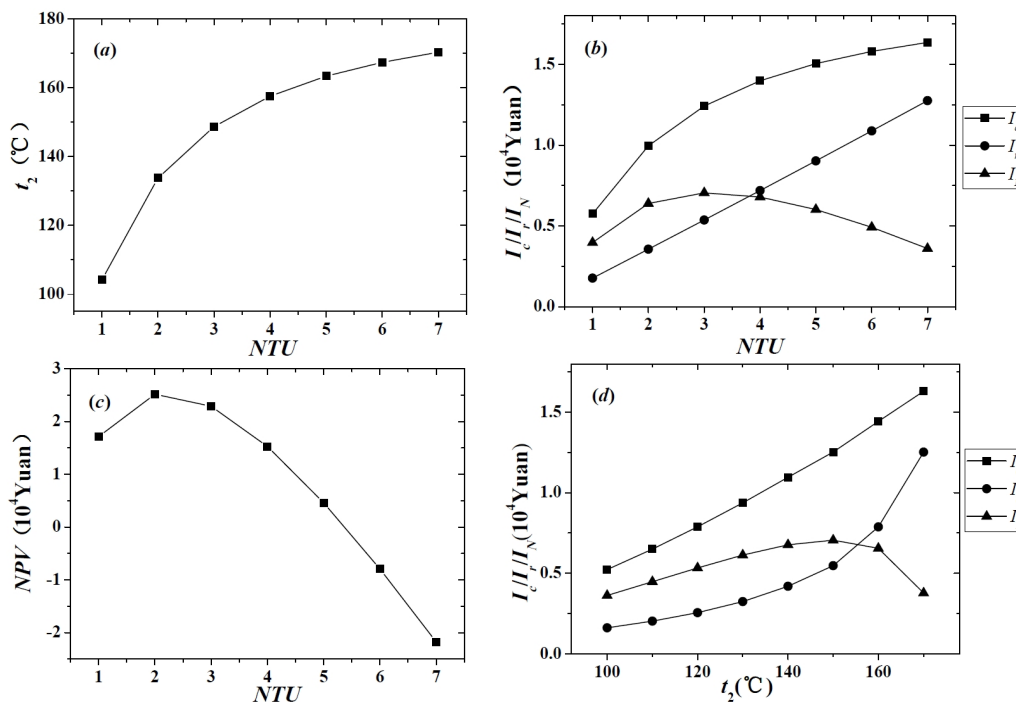


Fig.1. (a) The influence of t_2 by NTU . (b) The influences of I_c , I_r and I_N by t_2 . (c) The influence of NPV by NTU . (d) The influences of I_c , I_r and I_N by NTU .

With the increasing of NTU , the parameters t_2 , I_c and I_r grow. However, the parameters (I_N and NPV) rise firstly and then reduce, see Fig. 1 (a)-(b). For the parameter t_2 , when the value of NTU is more than 4 (i.e., $NTU>4$), t_2 rises slowly. It implies that the NTU cannot give more effect on t_2 , see Fig. 1(a). In addition, there is an optimal NTU around 2 which can get max I_N and NPV [see in Fig. 1(b) and (c)]. As is shown in Fig. 1(d), the change trends of the parameters I_c , I_r and I_N with the parameters t_2 are similar

to the ones of NTU versus I_c , I_r and I_N . Therefore, the maximum I_N can be gotten around $t_2=140^\circ\text{C}$, which corresponds to the optimal NTU . As a consequence, the maximum t_2 , NPV and I_N can be obtained by the optimal NTU .

By using NPV being the optimization object, we can get value of the optimal NTU is 2.19, thus we can calculate other major parameters like heat transfer area and air preheating temperature. The computed results of optimization design are listed in Table 3.

Table 3. Computed results in optimization design.

title	value
Heat transfer area	46.12 m ²
Air preheating temperature	137.32 °C
Net income per year	0.66×10 ⁴ Yuan/year
Initial cost	1.34×10 ⁴ Yuan/year
NPV	2.53×10 ⁴ Yuan/year

Conclusions

In this paper, we apply NTU as the intermediate parameters to analyze the optimal air preheating temperature by NPV method and finally obtain the optimization proposal.

As determining the optimal $NTU=2.19$, we get the maximum air preheating temperature $t_2=137.32^\circ\text{C}$ and heat transfer area of 46.12 m², which means we can get the highest residual income of $NPV=2.53\times 10^4$ Yuan/year in this air preheating temperature. Therefore, as an important tool, the NPV method can be used to optimize the waste heat exchanger.

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