Abstract

VOC (Volatile organic compound) emissions are harmful to human health and environment. Many industries rely on VOC thermal oxidation as a proven technique of VOC abatement. In VOC thermal oxidation, both the thermal oxidation and heat recovery are equally important. Heat recovery reduces the energy cost while the thermal oxidation fulfills the necessary VOC destruction. Recuperative Thermal Oxidizer and Regenerative Thermal Oxidizer are capable to fulfill both functions of thermal oxidation and heat recovery in VOC thermal oxidation process.

This work discussed the equipment costs of Recuperative and Regenerative Thermal Oxidizers, and also emphasized the importance of heat recovery in thermal oxidation process. Three parameters namely, Equipment Cost Factor (ECF), Heat Recovery Factor (HRF), and Equipment Cost against Heat Recovery (ECHR), were presented in the analysis of economics of equipment cost and heat recovery, in VOC thermal oxidation. The case study connected with Recuperative and Regenerative Thermal Oxidizers, provided a better understanding of the usage of the parameters ECF, HRF, and ECHR in the evaluation and selection of thermal oxidizer equipments.

1.  INTRODUCTION

Volatile organic compounds (VOC), which are harmful to human health and environment, are formed in the manufacturing processes in industries such as semiconductor industries, chemical plants, paint booths, printing industries, etc. Environmental authorities enforce stringent regulations on VOC air pollution control. As a result, industries are forced to adopt VOC abatement processes and systems, to effectively treat VOC emissions. Thermal oxidation is popular among industries as a proven technique of VOC abatement. In VOC thermal oxidation process, VOC or VOC laden air is thermally-treated (burned, oxidized, decomposed) by exposing them to higher temperatures of about 730-850°C. Raising the temperature of VOC laden air to such higher temperatures needs enormous amount of energy, especially when the airflow rates are in thousands of NCMH (normal cubic meters per hour). In such situations the cost of process operation becomes extremely expensive, unless a substantial amount (above 60%) of waste heat is recovered. Therefore energy (heat) recovery in thermal oxidation of VOC laden air becomes very much important.

When heat recovery is important, equipments named Recuperative, and Regenerative Thermal Oxidizers are used for VOC thermal oxidation. Recuperative Thermal Oxidizers (Recuperative TO) are used for heat-recovery-efficiency generally up to 60-70%, whereas regenerative thermal oxidizers (Regenerative TO) are used for heat-recovery-efficiency even exceeding 90%.

Though the thermal oxidizer is the key equipment meant for VOC destruction, there are other peripheral components integrated with the thermal oxidizer, as for the process viability & optimization. In VOC abatement systems in semiconductor industries, peripheral equipments such as concentrator (desiccant, or activated carbon made) is used to concentrate the VOC contents, and thereby to reduce the process-air volume. This reduced process air volume results in significant lowering of both equipment and operation cost. Because of the presence of the concentrator, additional heat exchanger is employed, to supply hot air to concentrator. Fig. 1 and Fig. 2 show the schematics of Recuperative-TO, and Regenerative-TO, and other peripherals (concentrator and fans are not shown).
A: RTO inlets; Heat media inlet gas (Heat degeneration tower)
B: Combustion chamber inlet; Heat media outlet gas (Heat degeneration tower)
D: Combustion chamber outlet; Heat media inlet (Heat regeneration tower)
E: RTO outlet; Heat media outlet (Heat regeneration tower)
F: Hot gas bypass from RTO combustion chamber for VOC DESORB process.
Z: Ceramic (heat media) bed height.

Fig. 1 Schematics of Recuperative-TO, and other peripherals (concentrator and fans are not shown).

Fig. 2 Schematics of Regenerative-TO and other peripherals (concentrator and fans are not shown).
2. EQUIPMENT COST

Equipments of thermal oxidation system with heat recovery, and peripheral components, could easily cost few hundred thousands of US$. The high cost is because of the sizes of the equipment and the expensive parts and materials used to withstand higher temperatures.

For comparison purposes, Table 1 presents some estimates for the costing of only Recuperative and Regenerative TO, for different capacities (excluding the peripheral components).

Table 1. Equipment costs (Recuperative and Regenerative TO) in US$, for different airflow capacities.

<table>
<thead>
<tr>
<th>Airflow capacity NCMH</th>
<th>Recuperative TO Cost/ (US$)</th>
<th>Regenerative TO of Cost/ (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1570</td>
<td>121,000</td>
<td>145,000</td>
</tr>
<tr>
<td>3140</td>
<td>139,000</td>
<td>169,000</td>
</tr>
<tr>
<td>4710</td>
<td>145,000</td>
<td>181,000</td>
</tr>
<tr>
<td>6280</td>
<td>160,000</td>
<td>203,000</td>
</tr>
<tr>
<td>7850</td>
<td>169,000</td>
<td>218,000</td>
</tr>
</tbody>
</table>

Efficiency(η)  η = 60%  η = 85%

* Where, \( \dot{q} \) is the “Per-NCMH heat requirement” needed to increase temperature of VOC laden air to thermal oxidation temperature.

3. EQUIPMENT HEAT RECOVERY

Total heat required for thermal oxidation process \( \dot{Q}_T \)

If recovered heat is \( \dot{Q}_R \) then \( \dot{Q}_T = \dot{Q}_R + \Delta \dot{Q} \)  (1)

Where \( \Delta \dot{Q} \) is the heat addition (like refill).

Energy recovery efficiency: \( \eta = \frac{\dot{Q}_R}{\dot{Q}_T} \)  (2)

By rearranging of (1), \( 1 = \frac{\dot{Q}_R}{\dot{Q}_T} + \frac{\Delta \dot{Q}}{\dot{Q}_T} \)  (3)

Then from (2) in (3), \( \Delta \dot{Q} = (1 - \eta)\dot{Q}_T \)  (4)

For given \( \dot{Q}_T \), and then by referring equation (4), when the recovery efficiency “\( \eta \)” is higher, the heat addition \( \Delta \dot{Q} \) becomes lower. Then, the energy cost will be lower, since the addition of new heat by burning fuel or electricity becomes lesser, when \( \eta \) is higher. Also, for given \( \dot{Q}_R \), and according to the equation (2), the increasing of recovery efficiency “\( \eta \)” results the lowering of the total heat \( \dot{Q}_T \). Hence, whatever the optimizing interest, whether it is \( \Delta \dot{Q} \) or \( \dot{Q}_T \), meeting of desired efficiency “\( \eta \)” will be the ultimate concern.

4. MODEL FOR THE EVALUATION OF EQUIPMENT COST AND HEAT RECOVERY

As an evaluation of equipment cost and heat recovery, in thermal oxidation of VOC laden air, the below parameters are suggested.

Equipment Cost Factor is used to reflect equipment cost against the cumulative amount of airflow handled during the time period of \( t \), ($/NCM), could be suggested as,

\( \text{ECF} = f(\$ , \dot{V}, t, \beta) \), as \( \beta \).

Heat Recovery Factor is used to reflect cumulative heat recovery against the cumulative amount of airflow, during the time period of \( t \), (kWh/NCM), could be suggested as,

\( \text{HRF} = f(\dot{Q}_R, \dot{V}, t, \beta) \), as \( \beta \).

Therefore \( \text{HRF} = f(\dot{Q}_R, \dot{V}) \) becomes

\( \text{HHR} = \frac{\dot{Q}_R}{\dot{V}} = \eta \dot{q} \)

Where,

\( \dot{q} \): Per-NCMH heat requirement needed to increase VOC laden air temperature to thermal oxidation temperature

\( \dot{V} \): Airflow in NCMH
t: Equipment nominal age in hours
\( \beta \): Usage time factor (ratio of actual operated hours to equipment age in hours”)

\( \$: \) Cost of equipment in US$

Equipment Cost against Heat Recovery (ECHR), as to reflects the cost of equipment against the heat recovery payback, ($/kWh), could be suggested as,

\( \text{ECHR} = \frac{\text{ECF}}{\text{HRF}} = \frac{\$}{\eta \dot{q} \dot{V} t \beta} \)  (8)

General comparison of ECHR for two thermal oxidizer equipments can be performed as follows.
ECHR for Equipment 1, \( ECHR_1 = \frac{ECF}{\text{HRF}}_1 = \left( \frac{\$}{\eta q V_1 \beta_1} \right) \),

ECHR for Equipment 2, \( ECHR_2 = \frac{ECF}{\text{HRF}}_2 = \left( \frac{\$}{\eta q V_1 \beta_2} \right) \).

Then, \( ECHR_2 > ECHR_1 \), and hence the equipment-1 can be considered as economically more favorable than Equipment-2.

Even in such analysis, Equipments-1 and 2 should not necessary to be of the same type. One can be Recuperative TO, and the other can be Regenerative TO. In such evaluations \( t \) can be considered as the guaranteed life time or expected usage of equipments.

According to the equation (6) and (8), ECF and ECHR improve (reduce) with the age of the thermal oxidizer, and with a higher usage time factor \( \beta \). Also according to equation (7), higher \( \eta \) and \( q \) values, improve both HRF (higher) and ECHR (lower).

5. CASE STUDY

By referring Table 1, for airflow of 6280 NCMH, equipment cost of 203,000 US$, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 85\% \), and for \( \beta = 100\% \), values of ECF, HRF, and ECHR for Regenerative TO can be shown as in Table 3.

Table 3 showing ECF, HRF, and ECHR for Regenerative TO for airflow of 6280 NCMH*, equipment cost of 203,000 US$, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 85\% \), \( \beta = 100\% \), and for different values of \( t \). *Ref. Table 1.

By referring Table 1, for airflow of 6280 NCMH, equipment cost of 203,000 US$, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 85\% \), and for \( \beta = 100\% \), values of ECF, HRF, and ECHR for Regenerative TO can be shown as in Table 3.

Table 4 showing ECF, HRF, and ECHR for Regenerative TO for airflow of 6280 NCMH*, equipment cost of 203,000 US$, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 85\% \), \( \beta = 100\% \), and for different values of \( t \). *Ref. Table 1.

By referring Table 1, for airflow of 43200hr, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 60\% \), \( \beta = 100\% \), ECF, HRF, and ECHR values for Regenerative TO can be shown as in Table 4.

Table 4 showing ECF, HRF, and ECHR for Regenerative TO for airflow of 43200hr (5 yrs), \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 60\% \), \( \beta = 100\% \). *Ref. Table 1.

By referring Table 1, for t=5x12x30x24=43200hr, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 60\% \), \( \beta = 100\% \), ECF, HRF, and ECHR values for Recuperative TO can be shown as in Table 4.

Table 4 showing ECF, HRF, and ECHR for Recuperative TO for airflow of 43200hr (5 yrs), \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 60\% \), \( \beta = 100\% \). *Ref. Table 1.

By referring Table 1, for airflow of 6280 NCMH, equipment cost of 160,000 US$, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 85\% \), and for \( \beta = 100\% \), values of ECF, HRF, and ECHR for Recuperative TO can be shown as in Table 2.

Table 2 showing ECF, HRF, and ECHR for Recuperative TO for airflow of 6280 NCMH*, equipment cost of 160,000 US$, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 85\% \), \( \beta = 100\% \), and for different values of \( t \). *Ref. Table 1.

<table>
<thead>
<tr>
<th>( t ) (hr/yr)</th>
<th>ECF</th>
<th>HRF</th>
<th>ECHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>8640 (1 yr)</td>
<td>0.0003741</td>
<td>0.425</td>
<td>0.008802</td>
</tr>
<tr>
<td>17280 (2 yrs)</td>
<td>0.0001871</td>
<td>0.425</td>
<td>0.004401</td>
</tr>
<tr>
<td>25920 (3 yrs)</td>
<td>0.0001247</td>
<td>0.425</td>
<td>0.002934</td>
</tr>
<tr>
<td>34560 (4 yrs)</td>
<td>0.0000935</td>
<td>0.425</td>
<td>0.002201</td>
</tr>
<tr>
<td>43200 (5 yrs)</td>
<td>0.0000748</td>
<td>0.425</td>
<td>0.001760</td>
</tr>
</tbody>
</table>

By referring Table 1, for t=5x12x30x24=43200hr, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 60\% \), \( \beta = 100\% \), ECF, HRF, and ECHR values for Recuperative TO can be shown as in Table 5.

Table 5 showing ECF, HRF, and ECHR for Regenerative TO for airflow of 6280 NCMH*, equipment cost of 160,000 US$, \( \dot{q} = 0.5 \text{kW/NCMH} \), \( \eta = 85\% \), \( \beta = 100\% \). *Ref. Table 1.
Table 2 and 3 shows the trend of the improvement of ECF and ECHR with time of usage, for both Recuperative and Regenerative TO. For this particular set of results, and for a same period of equipment usage, ECHR in Regenerative TO is better than that of Recuperative TO, though ECF is shown in the other way. However ECHR values of Recuperative TO can be better than that of Regenerative TO, for different time of usages.

Table 4 and 5 shows the ECF, and ECHR variations for different equipment capacities, for both Recuperative TO and Regenerative TO. Of the set of Recuperative Thermal Oxidizers, one with capacity of 7850NCMH is the most economical, where as the one with capacity of 4710NCMH is the least economical. Of the set of Regenerative Thermal Oxidizers, one with the capacity of 7850NCMH is the most economical, where as the one with capacity of 1570NCMH is the least economical. Of all the sizes of Recuperative and Regenerative Thermal Oxidizers, Regenerative TO with the capacity of 7850NCMH is the most economical, where as the Recuperative TO with the capacity of 4710NCMH is the least economical.

CONCLUSION

Analysis of equipment cost and energy recovery, in the selection and evaluation of thermal oxidizer equipments, was reviewed.

Values of $ and $\dot{q}$ could be adjusted to accommodate costs of the peripheral equipments and the other energy consumptions. Cost of the peripheral components could be directly added to the $ value. Other energy consumptions could be converted into cost equivalent burner energy units, before adding them to $\dot{q}$.

HRF and ECF could be considered as two independent parameters. By considering only one parameter will not give a proper view of the economy of usage. However the parameter ECHR which is the combination of two parameters of ECF and HRF would provide a better insight for the understanding of economy of the equipment. This ECHR evaluation could be useful for the users to choose more economical equipment, among many design proposals.

ACKNOWLEDGEMENT

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