Toward Eco Product Development with Qualitative and CAE Design Process - Case Study of Flame Guiding Module

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Abstract. Sustainable products become increasingly important for company in addressing eco-performance to satisfy global environmental regulations. Case study of flame guiding module reviewed design process and concerns related to the torch design. For enhancing flame height, the torch was embedded with an airflow guidance structure. The design process and design methodologies were investigated as an eco-design case study. Combine qualitative and CAE simulation were proposed to fulfil its main and auxiliary functions including reduction of impact during use. The design guidelines help prevent mistake arrangements, CAE helps understand combustion phenomenon. The flow field simulation enables fine tune of geometric design. Functional test and measurement are carried out to confirm the product features. On Eco-performance, we choose 5 items for evaluation the status of previous and redesign module, namely function need, low impact material, few manufacturing steps, low energy consumption, and safety. The radar diagram indicates that eco-performance of redesign module is better. Life cycle assessment calculated the carbon footprint of the manufacturing and processing stage with Eco-it. By using recycled steel in the flame module, it reduces raw material stage carbon footprint significantly.

1. Introduction
Products eco-design aims to enhance usage, emotional value, and reduce the environmental burden throughout the entire product life cycle. Many eco-design methodologies based on life cycle thinking have been developed [1, 2]. Eco-design products are assessed based on functional, economic, and ecological criteria to achieve sustainability [3, 4].

1.1. Checklist
The checklist is one of eco-design methodologies [5] support for the analysis of a product's impact on the environment to avoid missing those features. It provides relevant questions that need to be asked about environmental bottlenecks. Usually, it starts with a needs analysis to fulfill its main and auxiliary functions. With this method, a designer can work out systematically redesign tasks on part, function and product levels. The steps include [5]: (1) define the existing product, (2) systematically answer the questions from the list, per stage of the product’s life cycle, and (3) have improvement options as clearly as possible. The main strategies are (1) selection of low-impact materials, (2) reduction of material usage, and (3) modification of production techniques, and (4) reduction of impact during use.
1.2. CAE & Eco-design
The main target of flame module redesign is finding suitable parameters for enhancing natural convection. The heat transfer caused by fluids is expressed with the following equation:

\[ Q_w = h (T_w - T_f) \]  

(1)

where \( T_w \), \( T_f \) is the wall and fluid temperature. The heat transfer coefficient \( h \) depends on kind of fluid, its flow state, and the shape of the object. Computational fluid dynamics (CFD) techniques are foundation to predict airflow. Finite volume method (FVM) is a common approach used in CFD codes especially for large problems and source term dominated flows.

Sustainable future is an important driving force of innovation. The abilities of prediction and insight of problem make CAE simulation important in sustainable design. Designer used parametric optimization capabilities to design a car wheel hub that follows lines of force and avoids stress [6] with less material.

1.3. Qualitative guidelines
CAE does not necessarily solve the problem unless you find the right design. First of all, we need a basic understanding of the physical system, and then CAE detailed calculation steps support to get right parameters. Therefore, the designer also needs non-quantitative design guidelines.

For flow guidance design: the size and location of the opening shape need to be considered. Through the test and design changes, one can obtain the ideal airflow mode. Utilize the diversion port to guide the airflow in the ventilation path, reducing the occurrence of turbulence. Natural convection caused by negative pressure can bring into the air, to achieve an effective cooling cycle.

High surface temperature causes human risk. Careful considering the flow path can reduce the risk. The non-quantitative design guidelines can guide the initial concept of the proposal. The examples of the design guidelines are as follows [7, 8]:

- The mechanical elements must be demonstrated to a minimum useful lifetime of 20,000 hours.
- Thermal characterization should be carried out at the entire system level.
- Do not place the inlet of a blower directly downstream of the exhaust of another blower.
- Do not put two different blowers in series or in parallel unless the flow rates and head pressures in the system are balanced.
- Do not obstruct coolant flow, guide flow by means of splitters and turning vanes.
- Maximize the radii of turns in flow passages. Use gradual turns, enlargements, and contractions in flow passages.
- For free-convection, install cooling fins vertically. Do not place parts directly above high dissipating parts instead stagger them horizontally.

2. Case study of flame redesign
The case study reviews design process and concern on the torch. For enhancing flame height, the torch was embedded with an airflow guidance structure. Flame redesign process and design methodologies were investigated as an eco-design case.

2.1. Design procedure
Gas or Biofuel is chosen as fuel which is low oxygen consumption and capable of producing an ornamental flame with adjustable flame height. We built the digital model with CATIA solid modeling package. The digital model can be used to quickly build the tangible model by 3D printing. For simulation, digital model was discretized into small blocks (element), which can be set up the equation and boundary conditions. To solve the linear matrix equations, computer-aided engineering tool provide different solver depending on problem types, such as structural static stress or field distribution.
The prototype model can utilize for measuring actual physical parameters. The actual measured data and simulation results are compared to each other. We adjust the simulation parameters iteratively till meeting each other. When the parameters are confirmed, designer can use the digital model confidently to obtain design parameters. The major benefit of this development process is shorter cycle time through concept to the proof. Then manufacturing tradeoffs are also reviewed to confirm production feasible.

![Design flow](image)

**Figure 1. Design flow**

As shown in figure 1, the design guide help prevent mistake arrangements. CAD/ CAE are used to quickly realize the idea. The flow field simulation enables fine tune of geometric design. Functional test proof and confirm the product features, through a series of measurements such as thermal energy, flame height, contact temperature (glass and metal). After that, the checklist was reviewed to enable the modified concepts.

2.2. Simulation results

In the case of the flame redesign, the complicated phenomena make CAE simulation much harder as described here. 3D surface and structure of the module are used to calculate the flow channel outlet speed, outlet angle and exhaust flow rate. Flow channel analysis was performed using non-premixed combustion mode. With the alcohol fuel combustion equation, through the amount of combustion to determine “Is the amount of oxygen supply is sufficient?”

\[
C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O \tag{2}
\]

In non-premixed combustion, fuel and oxidizer enter the reaction zone in distinct streams [9]. This is in contrast to premixed systems, in which reactants are mixed at the molecular level before burning. Under certain assumptions, the thermochemistry can be reduced to a single parameter: the mixture fraction. The mixture fraction, is the mass fraction that originated from the fuel stream. In other words, it is the local mass fraction of burnt and unburnt fuel stream elements (C, H, etc.). Once mixed, the chemistry can be modeled as being in chemical equilibrium with the Equilibrium model, the Steady Laminar Flamelet model in which the microscopic element in the turbulent ensemble has the structure of an undisturbed laminar diffusion flame. The profiles of scalar properties provide an alternative thermochemical relationship to that of chemical equilibrium [9].

Analysis results of outlet angle and exhaust port velocity (figure 2) indicates the oxygen supply is sufficient. The XZ profile velocity chart (figure 3), the upwardly convection is on the outer edge of the cylinder. The streamline in overall flow line velocity diagram (Figure 3) is helically raised. Measured average temperature of the glass is 260° and that of outlet air is 505°. When the guide vane angle
varies from 40 to 44 degrees, results of exhaust port velocity (table 1) indicated transition zone gradually downward shifted. Table 2 is suggested parameters based on simulation and measurement.

**Figure 2.** Non-premixed flames, modelling and inlet open boundary

**Table 1.** Analysis results of exhaust port velocity

| Variable                  | entry value | Outlet value |
|---------------------------|-------------|--------------|
| Quantization value        |             |              |
| Amount of airflow         | 3.1995(g/sec) | 3.278(g/sec) |
| Oxygen content ratio      | 0.232       | 0.1948       |
| Average speed             | 0.120(m/sec) | 1.273(m/sec) |

**Figure 3.** Outlet angle and exhaust port velocity analysis results

**Table 2.** Suggestions parameters

| Variable                        | sensitivity | suggestions |
|--------------------------------|-------------|-------------|
| Guide vane angle (30-60deg)     | High        | 40          |
| Glass tube height (30 to m)     | Medium      | 36          |
| length (3cm)                    | Low         | >40         |
| Number of leaves                | Low (12-24) | 20          |
2.3. Prototyping & measurement
The redesign of the flame height is much higher than the previous. Although the low diversion angle (below 40 degrees) caused outlet oxygen ratio slightly increased (complete flammability), the benefits are small (figure 4). Flame ornament ability decrease for the low angle, so the skew angle is recommended to be more than 40°. Prototyping models (figure 5) are used in the test to find better parameters. The main bodies of the ring and spiral material are steel, which was the high-temperature measured zone.

According to the regulations, we surveyed the most stringent CSA specification for the stove. There is spec. about the glass part of the open fire, but there is no high-temperature limit. Manufacture need warning mark on the glass. Thermal imager measurement showed the glass temperature of re-design is lower than related products. It revealed the effectiveness of the CAE design flow.

Figure 4. Measured flame for different skew angle of guide vane. Flame height is 35 - 44 cm, much higher than the previous design (15 ~ 22). Aluminium castings and iron plate metal, metal contact temperature is not higher than 60 degrees. Transparent parts: heat-resistant glass can be more than 600 degrees.

Figure 5. Prototyping model shown detail of the guide vane
3. Eco checklist and LCA

3.1. Checklist
According to [6], we select some keywords as follow: needs, fulfills its main and auxiliary functions, stage of the product’s life cycle, options for improvement, low-impact materials, reduction of material usage, optimization, reduction of impact during use. By grouping related item, we choose 5 items for evaluation the status of previous and redesign module, namely function need, low impact material, few manufacturing steps, low energy consumption, and safety. The radar diagram shown in figure 6 indicates that eco-performance of redesign module is better than the previous product.

![Radar diagram showing eco-performance of redesign module](image)

**Figure 6.** Eco-performance of redesign module

With a similar amount of material, redesign does not use the active device to push air and achieve substantial functional enhancement. Being appropriate combustion conditions, the redesign does not result in incomplete combustion of carbon monoxide. This is a significant reduction of the poisoning probability. No moving parts cause lower failure probability and product life increasing. All materials (figure 7) are recyclable also reduce the environmental impact. Explore the reason of the significant improvement, for "fulfills its main and auxiliary functions", comes with the qualitative design guidelines and CAE on the combustion phenomenon. Design process helped fully explore the "options for improvement". Through the model test, modify and verify the simulation parameters, which enable "optimization" and achieve “reduction of impact during use”.

3.2. LCA
Green design -the industry trend promoted low-carbon production, to enhance the competitiveness. We selected life cycle assessment (Eco-indicator 99) [10] using carbon footprint as an indicator, category from cradle to the door. The module of case study contains the raw materials (mining and manufacturing), transportation, processing stage till the module is completed [11], as shown in figure 7. Carbon footprints of the manufacturing stage are summarized with Eco-it in table 3 and 4. Flame module’s total carbon footprint is 23.4 KgCO₂. If we the use recycled steel in future, it will reduce raw material stage carbon footprint significantly.
**Figure 7.** Parts of redesign module [12], where (16, 10) is flow guidance rib and channel, (L) indicate skew angle, (10) is module, and (20) is base frame.

**Table 3.** Raw material carbon footprint: 9.83 (KgCO₂)

| Part No. | Name        | Quantity | Weight (Kg) | Material     | Footprint |
|----------|-------------|----------|-------------|--------------|-----------|
| 1        | Glass       | 1        | 0.921       | Glass        | 0.51      |
| 2        | Core        | 1        | 0.783       | cast iron    | 1.16      |
| 3        | Disc        | 1        | 0.402       | White iron   | 1.9       |
| 4        | Shell       | 1        | 2.082       | cast iron    | 3.1       |
| 5        | Wick        | 3        | 0.011       | Stainless steel | 0.16 |
| 6        | Wick        | 1        | 0.053       | White iron   | 0.25      |
| 7        | Light body  | 1        | 0.108       | White iron   | 0.51      |
| 8        | Base        | 1        | 1.351       | cast iron    | 2.0       |
| 9        | Foot pad    | 4        | 0.02        | rubber       | 0.24      |

**Table 4.** Processing carbon footprint: 13.6 (KgCO₂)

| Part No. | Name          | Quantity | Weight (Kg) | Material      | Footprint |
|----------|---------------|----------|-------------|---------------|-----------|
| 1        | Glass tube    | 1        | 0.921       | Annealing     | 0.168     |
| 2        | Core          | 1        | 0.783       | Casting casting | 2.4       |
| 3        | Disc          | 1        | 0.402       | Stamping sheet | 0.35      |
| 4        | Shell         | 1        | 2.082       | Casting casting | 6.4       |
| 5        | Wick          | 3        | 0.011       | Coil, stamping | 0.041     |
| 6        | Wick          | 1        | 0.053       | Inject molding | 0.046     |
| 7        | Light body    | 1        | 0.108       | Inject molding | 0.094     |
Total carbon footprint in the processing stages 13.6 Kg. Transport phase Carbon footprint is parts weight (T) *Transport distance (km). The transport phase takes into account the carbon footprint of the parts delivered to the assembly plant using a truck. The distance was estimated by the shipped plans with Google Map. Due to the factory is cluster locate in Taichung area, total carbon footprint in the transport phase is 0.4.

4. Conclusions
The concept for sustainable products aims to enhance usage, emotional and economic value, and reduce the environmental burden throughout the entire product life cycle. It becomes increasingly important for company in addressing eco-performance to satisfy global environmental regulations. In this article, combine qualitative and CAE design process were proposed for fulfills its main and auxiliary functions and reduction of impact during use. The case study shows successful outcomes. Design process helps understand combustion phenomenon and fully explore the "options for improvement". Through the model test, modify and verify the rationality of the simulation parameters, engineers are able to select proper parameters and achieve “reduction of impact during use”.

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