Estimation Method of Pollutant Emissions in Certain Aircraft Flight

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Abstract: This paper intends to calculate the emissions of pollutants during the route flight quantitatively. In this paper, the flight dynamics model of the climb, cruise and descent phases are established respectively. Then, the pollutant emission estimation model of the aircraft is established based on the ICAO LTO model and the benchmark emissions data of engine manufacturers. Take certain civil aviation aircraft into account, a typical route is simulated, then the emissions of various pollutants at different flight stages are calculated and analyzed. Finally, several typical cruise strategies are selected for further comparative analysis. The results show that CO₂ and NOₓ are the main pollutants during route flight. In addition, the pollutant emissions during the cruise phase are the highest, and the pollutant emissions during route flight can be effectively reduced by choosing the appropriate cruise strategy. The research results can be used to quantify and analyze the impact of flight performance optimization on civil aviation energy conservation and emission reduction, so as to better satisfy the requirements of green operations while ensuring flight safety.

Keywords: environmental engineering; route flight; fuel consumption; pollutant emissions

1. Introduction

With the rapid development of the civil aviation industry, pollutants such as CO₂, NOₓ, CO, HC and SO₂ generated by civil aircraft in flight have also attracted more and more attention from the industry and the public. According to the distribution area of emissions, the environmental impact of aircraft engines can be divided into two major areas: the global greenhouse effect and air quality problems within the airport area [1]. In order to control and reduce the impact of the aviation industry on the greenhouse effect, the EU has incorporated the airline's aircraft carbon emissions into the carbon emissions trading system [2]. Although there are still objections to who should be the charging entity, the air industry has agreed that the aircraft emissions should be controlled by market means. The International Civil Aviation Organization (ICAO) has also begun to organize experts to discuss and study global aviation emissions trading mechanisms and control issues based on market models. At the same time, Committee on Aviation Environmental Protection (CAEP) has also established a carbon emission assessment indicator system for civil aviation transportation and design in 2013 [3].

Accurate and rapid estimation of aircraft pollutant emissions is fundamental to emission control and environmental impact assessment, and is also the key to energy efficiency assessment of air traffic control. Based on the engine manufacturer's certification data, the International Civil Aviation
Organization (ICAO) has developed an emission database for various aircraft types, which uses the standard take-off and landing cycle (LTO) to calculate the CO, HC and NOx emissions for taxi, take-off, climb, approach and landing phases of aircraft below 1 000 m within the airport area. However, the route emission which is account for nearly 80% time of the flight is not considered [4]. Based on the ICAO emission model, Sherry [5] used discrete data to improve the estimation accuracy by study the increase of airport pollutant emissions when reducing thrust. In order to estimate the impact of actual flight and meteorological conditions on emissions, Boeing proposed the BM2 method to implement the correction of the ICAO model [6], and made a basic study for accurate estimation of pollutant emissions in flight.

Based on the BM2 method, Turgut et al. [7] proposed a method for evaluating the NOx distribution in different directions during the take-off and climb phases of flight. Based on the Australian air traffic control record in 2008, Pham et al. [8] established a 4D emission database list with precision unit of 1 × 1 × 1 000 ft. Mitchell [9] assessed the environmental impact of the departure operation under the speed limit. According to the ICAO database, the BM2 model and the Basic Aircraft Data (BADA) model, the European Air Traffic Control Administration developed the Advanced Emission Model (AEM) to estimate actual emissions data based on 4D track data [10]. Wei Zhiqiang et al. [11], estimated the different pollutant emissions in each flight phase based on the established emission index BM2 correction model in 2008.

In order to consider the impact of non-carbon pollutant emissions, Cook et al. [12] studied the weight relationship between different pollutants in 2009, proposed the concept of dynamic cost index with emission costs, and used it for flight delay analysis. Schumann [13] established route optimization methods based on trail cloud and fuel consumption, in order to minimize the environmental impact of flight operations. Cruise is the major flight phase of a civil aircraft, which contributes the vast majority of fuel consumption, flight time and pollutant emissions. Wei Zhiqiang et al. [14] established a model of pollutant emission and optimization during the cruise phase, trying to reduce the impact of emissions by optimizing flight parameters.

This paper studies the estimation method of aircraft energy consumption and emissions based on flight dynamics model. Based on ICAO's LTO model, engine manufacturer's baseline emissions data, and Boeing's BM2 model, an aircraft fuel consumption and pollutant emissions estimation model covering all phases of flight was constructed. Visual Studio programming was used to calculate aircraft performance parameters and pollutant emissions at different phases. Based on the above method, a typical route is taken into account for calculation and analysis, and the pollutant emissions under different cruise modes are compared and analyzed in order to consider the effect of aircraft performance optimization on energy saving and emission reduction while ensuring the safe operation of civil aviation.

2. Flight dynamics model
The flight route mainly includes climb, cruise and descent phases. Based on the established flight dynamics model at each stage, the flight parameters of each flight state and the corresponding pollutant emissions can be calculated.

2.1 Climb Phase
When the aircraft is during en-route climbing, the external forces received are engine thrust $F_N$, Drag $D$, lift $L$, and gravity $W$. Its dynamic equation is as follows:

$$\frac{w}{g} \frac{dV}{dt} = F_N \cos \alpha - D - W \sin \theta$$

$$\frac{w}{g} \frac{d\theta}{dt} = F_N \sin \alpha + L - W \cos \theta$$

(1)

where $\alpha$ is the angle of attack; $\theta$ is the climb track angle; $V$ is the flight speed; $t$ is the flight time. During the en-route climb, the angle of attack is relatively small, then $\sin \alpha \approx 0$, $\cos \alpha \approx 1$.

Climb rate formula is as follow:
\[ \frac{r}{c} = \frac{dh}{dt} = V \sin \theta \]  

Substituting formula (1) into formula (2), we get:

\[ \frac{r}{c} = \frac{v_N - v}{\frac{v}{g \frac{dh}{dt}}} \]  

(3)

where \( 1 + \frac{v_{av}}{g \frac{dh}{dt}} \) is the acceleration factor.

Climb time:

\[ \Delta t = t_2 - t_1 = \frac{h_2 - h_1}{(r/c)_{av}} = \frac{\Delta h}{(r/c)_{av}} \]  

(4)

where \( \Delta t \) is the climb time used by the aircraft to climb the altitude \( \Delta h \); \( (r/c)_{av} \) is the average climb rate from \( h_1 \) to \( h_2 \) during the time \( \Delta t \).

Under non-standard atmospheric conditions, the true height (geometric height) is not equal to the air pressure height. \( \Delta t \) can be obtained from the relationship between geometric height and air pressure height. The calculation formula is as follows:

\[ \Delta t = \left( \frac{h_{2p} - h_{1p}}{(r/c)_{av}} \right) \left( \frac{T_{ns}}{T_{std}} \right) \]  

(5)

Then the total climb time is:

\[ t = \sum \Delta t \]  

(6)

Where \( T_{ns} \) and \( T_{std} \) are the absolute temperatures at the non-standard atmosphere and the standard atmosphere, respectively.

The climb track angle \( \theta \) of a civil airliner is very small, i.e. \( \cos \theta \approx 1 \), then the horizontal distance to climb a short altitude is:

\[ \Delta S = V_{avg} \Delta t \]  

(7)

where \( V_{avg} \) is the average true airspeed of climb from \( h_1 \) to \( h_2 \) during \( \Delta t \).

The total horizontal distance of the climb:

\[ S = \sum \Delta S \]  

(8)

Fuel consumption:

\[ \Delta F = W_{favg} \times \frac{\Delta t}{60} \]  

(9)

where \( W_{favg} \) is the average fuel flow for the selected altitude intervals.

The total fuel consumption:

\[ F = \sum \Delta F \]  

(10)

2.2 Cruise Phase

Assume the aircraft can meet the conditions of straight and horizontal flight at a constant speed at each moment, and the following dynamic equations are obtained:

\[ \begin{cases} F_N \cos \alpha - D = 0 \\ W - D - F_N \sin \alpha = 0 \end{cases} \]  

(11)

Assume the aircraft maintains a level flight when cruising in static atmosphere, then the lift and the gravity of the aircraft could be balanced, i.e.:

\[ L = W = \frac{1}{2} \rho V^2 C_L S_w = \frac{1}{2} \rho_0 M^2 a_0^2 \delta C_L S_w \]  

(12)

where \( \rho \) is the air density at the local altitude, \( C_L \) is the lift coefficient, \( S_w \) is the wing area, \( \rho_0 \) is the air density at standard sea level, \( a_0 \) is the speed of sound at standard sea level, and \( \delta \) is the pressure ratio at the local altitude.

2.3 Descent Phase

Descent rate equation:

\[ \frac{r}{d} = - \frac{dh}{dt} = V \sin \theta \]  

(13)
Flight dynamics equation:
\[
\begin{align*}
F_N - D + W \sin \theta - \frac{W}{g} \left( \frac{dV}{dt} \right) &= 0 \\
L + \frac{W}{g} V \left( \frac{d\theta}{dt} \right) - W \cos \theta &= 0
\end{align*}
\] (14)

Considering that when the aircraft descends, the rate of change of the descent angle is small, hence \( \frac{d\theta}{dt} \approx 0 \), and the normal descent angle is small, hence \( \cos \theta \approx 1 \), then \( L \approx W \).

The descent time is:
\[
\Delta t = t_2 - t_1 = \frac{\Delta h}{(r/d)_{avg}} = \frac{(h_{p2} - h_{p1}) T_{ns}}{(r/d)_{avg}}
\] (15)

The horizontal distance during the descent is:
\[
\Delta S = V_{avg} \Delta t
\] (17)
\[
S = \sum \Delta S
\] (18)

3. Pollutant emission calculation model

3.1 ICAO emission index and calculation model

Through statistical analysis of the take-off and landing data for each aircraft type, the International Civil Aviation Organization (ICAO) defines a standard take-off and landing cycle (LTO), including four phases of approach landing, taxiing, take-off and climb. On this basis, engine manufacturers provide emission index data for International Standard Atmosphere Model (ISAM) on sea level based on flight test data. The baseline emissions for certain aircraft with 17GE180-Genx-1B76A/P2 engine is shown in Table 1 (Sample) [15].

| Flight Phase     | Time /s | Thrust Level /% | Fuel Flow /kg·s⁻¹ | NOₓ | HC   | CO   | SO₂ | CO₂ |
|------------------|---------|-----------------|-------------------|-----|------|------|-----|-----|
| Take-Off         | 0.7     | 100             | 2.790             | 0.04690 | 0.0003 | 0.0005 | 0.001 | 3.15 |
| Take-Off Climb   | 2.2     | 85              | 2.262             | 0.02678 | 0.0002 | 0.0009 | 0.001 | 3.15 |
| Approach Landing | 4.0     | 30              | 0.709             | 0.01178 | 0.0004 | 0.00153 | 0.001 | 3.15 |
| Taxiing          | 26.0    | 7               | 0.223             | 0.05040 | 0.0036 | 0.01344 | 0.001 | 3.15 |

According to the definition of the above emission index, an emission calculation model can be obtained.
\[
E_{m,i} = n t_i I_{m,i} F F_i
\] (19)

where \( m \) is the type of pollutant; \( i \) is the flight time; \( E_{m,i} \) is emission of \( m \) pollutants at time \( i \), kg; \( n \) is the number of engines; \( t_i \) is the flight time step, s; \( I_{m,i} \) is the emission index; \( F F_i \) is the fuel flow.

3.2 Fuel flow correction model

The baseline flight state is the flight state assumed to meet the airworthiness certification, which is different from the actual flight state of the aircraft. Therefore, it is necessary to amend the emission index according to actual flight conditions to obtain more accurate pollutant discharge costs. When the types of aviation fuel are specified, the CO₂ and SO₂ emission index is independent of other factors and free of corrections. Since the actual cruise state of the aircraft is different from the baseline flight state, the other pollutant emission index needs to be corrected according to ICAO's BM2 method, in order to consider the impact of cruise parameters such as fuel flow, flight altitude, temperature deviation etc.
1) Correct the fuel flow. Firstly, the fuel flow of the aircraft needs to be converted to the modified fuel flow at ISA and sea level.

2) Calculate the emission index. ICAO provides thrust ratings and emission index for four typical flight conditions, but in actual flight, the emission index would be different from the Table 1 due to the difference between the aircraft's flight status and the ICAO data validation basis. So, the baseline emission index for each pollutant is calculated using a piecewise linear fit with the modified fuel flow based on Table 1.

3) Amend the emission index. The aircraft's emission index is also related to flight altitude, flight speed, atmospheric temperature and humidity.

The specific correction process is shown in Figure 1.

![Flow chart of fuel flow correction model](image)

**Figure 1.** Flow chart of fuel flow correction model

4. Example Analysis

4.1 Calculation and analysis of pollutants on a typical route

Taking a typical route as an example, the flight parameters of the entire route are calculated using the flight dynamics and the pollutant emission model, in order to get flight distance, flight time, fuel quantity and emissions of each pollutant in each flight phase. The calculation conditions are as follows: the flight distance is 9000km, the initial weight of the aircraft is 230,000kg, the temperature deviation is 0°C, the climb strategy is constant speed / equal Mach number (250kt / 300kt / 0.8 / 0.85) climbing, and the cruise strategy is step cruise with fixed Mach number (FL370- FL410 / M0.85), the descent strategy is symmetric to the climb. The detailed calculation results are shown in Table 2.

**Table 2.** Aircraft performance parameters and emissions calculation results on a typical route

| Flight phase | Flight distance /km | Time/s | Fuel/kg | CO₂/kg | NOₓ/kg | CO/kg | HC/kg | SO₂/kg |
|--------------|---------------------|--------|---------|--------|--------|-------|-------|--------|
| Climb        | 336.60              | 1560.77| 4737.98 | 14948.33 | 96.13 | 2.03 | 0.18 | 4.74 |
| Cruise       | 8399.40             | 33489.38 | 51586.81 | 162756.40 | 525.77 | 125.94 | 3.80 | 51.59 |
| Descent      | 264.00              | 1367.17| 468.35  | 1477.64 | 1.98   | 15.51 | 0.42 | 0.47  |
| Sum          | 9000.00             | 36417.32 | 56793.14 | 179128.40 | 623.88 | 143.49 | 4.40 | 56.79 |
From the aspect of pollutant emissions, CO\textsubscript{2} emissions are the most in the entire route, followed by NO\textsubscript{x}, and the emission of CO, SO\textsubscript{2} is relatively small and HC emission is the least. From the aspect of flight phase, the emissions of pollutants during the cruise phase are the highest. For CO\textsubscript{2}, NO\textsubscript{x}, and SO\textsubscript{2}, the emissions during the climbing phase are greater than those during the declining phase, while CO and HC are the opposite. The calculation results show that the pollutant emissions are different in different flight stages. For the cruise stage with the largest emissions, the cruise parameters can be optimized to reduce the pollutant emissions of the entire route.

4.2 Impact of cruise strategy on pollutant emissions

The aircraft performance parameters and emissions at different cruise altitudes are calculated and analyzed based on the calculation model established. Table 3 shows the detailed calculation results at different cruise altitudes. The rest of the calculation conditions are the same as in Section 4.1.

### Table 3. Aircraft performance parameters and emissions at different cruise altitudes

| Cruise Strategy                  | Phase  | Distance /km | Time/s  | Fuel/kg | CO\textsubscript{2}   | NO\textsubscript{x} | CO     | HC      | SO\textsubscript{2} |
|----------------------------------|--------|--------------|---------|---------|-----------------------|---------------------|--------|---------|-------------------|
| Step Cruise (FL350-FL410/M0.85)  | Climb  | 260.63       | 1255.57 | 4066.18 | 12828.80              | 86.94               | 1.39   | 0.14    | 4.07              |
|                                  | Cruise | 8475.19      | 3374.77 | 5200.37 | 164071.96             | 538.45              | 125.04 | 3.77    | 52.00             |
|                                  | Descent| 264.12       | 1367.89 | 468.60  | 1478.43               | 1.99                | 15.62  | 0.42    | 0.47              |
|                                  | Overall| 8999.95      | 36369.23| 56538.56| 178379.16             | 627.39              | 142.05 | 4.33    | 56.54             |
| Fixed Altitude Cruise (FL350/M0.85) | Climb  | 260.63       | 1255.57 | 4066.18 | 12828.80              | 86.94               | 1.39   | 0.14    | 4.07              |
|                                  | Cruise | 8512.34      | 33771.91| 52697.02| 166259.10             | 564.08              | 113.09 | 3.51    | 52.70             |
|                                  | Descent| 227.06       | 1219.63 | 428.48  | 1351.85               | 1.86                | 12.73  | 0.34    | 0.43              |
|                                  | Overall| 9000.03      | 36247.11| 57191.68| 180439.75             | 652.89              | 127.21 | 4.00    | 57.19             |
| Fixed Altitude Cruise (FL370/M0.85) | Climb  | 336.60       | 1560.77 | 4737.98 | 149483.33             | 96.13               | 2.03   | 0.18    | 4.74              |
|                                  | Cruise | 8424.70      | 33590.26| 51670.16| 163019.35             | 530.62              | 122.87 | 3.70    | 51.67             |
|                                  | Descent| 238.67       | 1266.15 | 441.00  | 1391.36               | 1.90                | 13.58  | 0.37    | 0.44              |
|                                  | Overall| 8999.97      | 36417.18| 56849.13| 179359.01             | 628.65              | 138.48 | 4.25    | 56.85             |

Table 3 shows that the cruise strategy does have obvious impact on the time and pollutant emissions. Fixed altitude cruise (FL350 / M0.85) offers the least flight time, yet the step cruise (FL350-FL410 / M0.85) gives the least fuel consumption and CO\textsubscript{2}/NO\textsubscript{x} emissions. Therefore, given the same flight Mach number, the pollutant emissions under step cruise can be reduced up to 1.14% of CO\textsubscript{2}/SO\textsubscript{2}, and 3.91% of NO\textsubscript{x} compared with the cruise at a fixed altitude.

Further analysis of the impact of cruise Mach number on pollutant emissions during route flight is carried out. Aircraft performance parameters and emissions are calculated at different cruise Mach numbers. The other calculation conditions are the same as in Section 4.1. Table 4 shows the detailed calculation results under different cruise Mach numbers.

### Table 4. Aircraft performance parameters and emissions at different cruise Mach numbers

| Cruise Strategy                  | Phase  | Distance/km | Time/s  | Fuel/kg | CO\textsubscript{2}   | NO\textsubscript{x} | CO     | HC      | SO\textsubscript{2} |
|----------------------------------|--------|--------------|---------|---------|-----------------------|---------------------|--------|---------|-------------------|
| Fixed Altitude Cruise (FL350/M0.8) | Climb  | 260.63       | 1255.57 | 4066.18 | 12828.80              | 86.94               | 1.39   | 0.14    | 4.07              |
|                                  | Cruise | 8518.91      | 35910.35| 52026.38| 164143.23             | 528.54              | 132.67 | 3.70    | 52.03             |
|                                  | Descent| 220.46       | 1312.59 | 451.41  | 1424.20               | 1.85                | 12.17  | 0.33    | 0.45              |
|                                  | Overall| 9000.00      | 38478.50| 56543.97| 178396.23             | 617.33              | 146.23 | 4.17    | 56.54             |
| Fixed Altitude Cruise            | Climb  | 260.63       | 1255.57 | 4066.18 | 12828.80              | 86.94               | 1.39   | 0.14    | 4.07              |
|                                  | Cruise | 8519.09      | 34822.90| 52341.15| 165136.33             | 545.85              | 122.95 | 3.58    | 52.34             |
Fixed Altitude Cruise (FL350/M0.85)

|            | Descent | Overall | Climb | Cruise | Descent | Overall |
|------------|---------|---------|-------|--------|---------|---------|
| Descent    | 220.27  | 1311.61 | 451.07| 1423.13| 1.81    | 12.10   |
| Overall    | 8999.99 | 37390.08| 56858.39| 179388.22| 634.61 | 136.44 |
| Climb      | 260.63  | 1255.57 | 4066.18| 12828.80| 86.94  | 1.39    |
| Cruise     | 8512.34 | 33771.91| 52697.02| 166259.10| 564.08 | 113.09 |
| Overall    | 9000.03 | 36367.11| 57221.68| 180534.40| 652.89 | 127.21 |

As can be seen from Table 4, FL350 / M0.85 offers the least flight time, yet FL350 / M0.8 obtains the least fuel consumption and CO₂, NOₓ, SO₂ emissions, and FL350 / M0.85 gets the least CO and HC emissions. Because CO₂ and NOₓ are the main pollutants during flight, at the same cruising altitude, the pollutant emissions can be reduced up to 1.18% of CO₂, SO₂ and 5.45% NOₓ under low flight Mach numbers compared with high flight Mach numbers.

5. Conclusion

Based on the ICAO LTO model and Boeing’s BM2 method, this paper constructs an aircraft engine emissions estimation method. Taking certain aircraft as example, the performance simulation of typical route is carried out to calculate the flight performance parameters and pollutant emissions during different flight phases. In addition, pollutant emissions under different cruise strategies are compared and analyzed.

The conclusion is summarized below:

1. CO₂ emissions account for an absolute proportion of various pollutants, exceeding 99%, followed by NOₓ, CO, SO₂, and HC.
2. Pollutants are emitted mostly during the cruise phase during route flight.
3. Under the same flight Mach number, the step cruise can effectively reduce the pollutant emissions during route flight compared with the fixed cruise strategy.
4. Flying at the same altitude, the low Mach number emits less pollutants compared with the high Mach number.

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