Technical Paper
Journal of Aerospace System Engineering
Vol.14, No.4, pp.40-46 (2020)

EISSN 2508-7150
http://dx.doi.org/10.20910/JASE.2020.14.4.40

Evaluation of Fuel Consumption of B747-400 in Short-range Flight with Catapult Assist

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Abstract

Recently, the aviation industry has sought to reduce its carbon usage in aircraft operations. Specifically, the industry is proceeding with the development of ultra-large turbofan engines and the development of hybrid electric engines to reduce the fuel consumption of aircraft. In one case, Airbus is developing as its future goal an aircraft with a short take-off distance that uses a catapult. In this study, when a b747-400 aircraft with two of the four engines removed was tested using a catapult, its fuel consumption was compared with that of the original aircraft. Fuel consumption was calculated using the mass flow consumption formula. Further, the aircraft L/D ratio caused by engine removal was interpreted using the CFD Tool, Ansys Fluent. The results showed that the lift ratio was improved by about 7% and that the fuel efficiency was improved by about 14%.

Key Words: Catapult, TSFC, Lift-drag ratio, MTOW, Breguet Equation, CFD

1. Introduction

As climate change issues have recently emerged internationally, efforts to reduce greenhouse gases have been actively conducted throughout the entire industry. The ICAO estimates that CO_2 emissions in the international aviation sector currently account for about 2% of global CO_2 emissions, but as shown in Fig. 1, carbon dioxide emissions will increase more than three times by 2050.

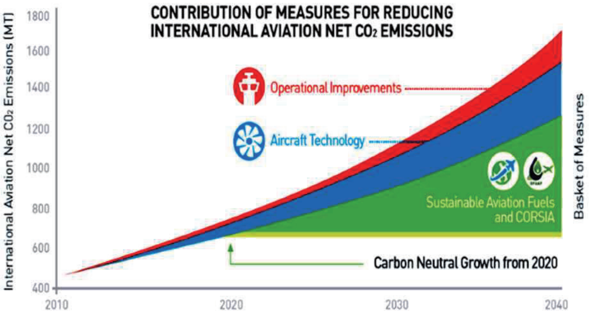

Fig. 1 Carbon Emission Prediction [1]

In response to this, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was signed with the goal of improving fuel efficiency by 2% per year through 2050. CORSIA is a system that involves freezing greenhouse gas emissions from international air transportation to 2020 levels and allows airlines that have exceeded these levels to purchase and offset emissions in the carbon market. Therefore, the aviation industry is making various efforts to improve aircraft performance through methods such as composite material operation, aerodynamic structure improvement, flight efficiency using AI, air traffic management and airport improvement, alternative fuel development, and electric turbofan engine development [1].

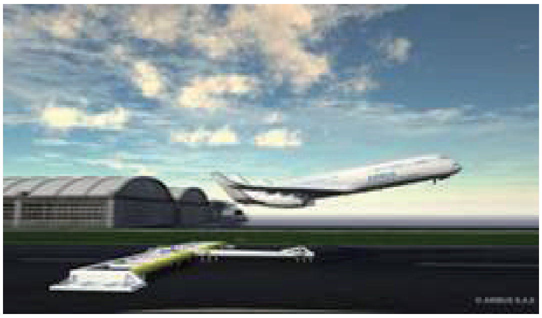

Fig. 1 Airbus Catapult Concept Design [2]

Among them is a concept by Airbus, which, as shown in Figure 2, is currently developing a rolling platform for

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Received: May 29, 2020 Revised: Jul. 03, 2020 Accepted: Jul. 07, 2020

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runways with the goal of taking off using a catapult. According to Airbus, since the aircraft using the platform will have an assisted take-off, it will rise steeply to minimize noise and reach an efficient cruising altitude faster, meaning it will consume less fuel than conventional aircraft. Therefore, to examine the effect of fuel consumption when operating an aircraft using a catapult, this paper compared the fuel consumption effect that exists when operating with the assistance of a catapult after removing two of the four engines of the B747-400 aircraft. Further, since this paper focuses on mathematically predicting the verification of ideas to improve fuel efficiency when flying with a catapult rather than commercialization, the increase in thrust and increase in structure caused by the catapult were not considered for simplification of the formula [2].

2. Modeling Condition

2.1 Fuel Consumption Equation

The amount of fuel to be used by an aircraft must be calculated according to various operating circumstances, but due to a lack of data, it is generally estimated using the Breguet formula. When two aircraft with the same operating speed have the same operating distance, the fuel consumption is the same as Eq. (1) when summarized using the Breguet formula [3].

$$\left(\frac{L}{D}\right)_1 \cdot \ln\left(\frac{m_1}{m_2}\right)_1 \cdot \frac{T}{\dot{m}_f} \cdot \frac{u}{g} = \left(\frac{L}{D}\right)_2 \cdot \ln\left(\frac{m_1}{m_2}\right)_2 \cdot \frac{T}{\dot{m}_f} \cdot \frac{u}{g} \quad (1)$$

If Eq. (1) is solved for the L/D of an aircraft with improved fuel efficiency, it is as follows.

$$\left(\frac{L}{D}\right)_2 = \left(\frac{L}{D}\right)_1 \cdot \left[\ln\left(\frac{m_1}{m_2}\right)_1 / \ln\left(\frac{m_1}{m_2}\right)_2\right] \quad (2)$$

Since the initial fuel quantity of the existing aircraft is fixed, solving the equation yields Eq. (3):

$$\therefore \ln\left(\frac{m_1}{m_2}\right)_1 > \ln\left(\frac{m_1}{m_2}\right)_2, \left(\frac{L}{D}\right)_2 > \left(\frac{L}{D}\right)_1 \quad (3)$$

According to Eq. (3), since it is assumed that two aircrafts make flights at the same range, a model with a reduced fuel load must be accompanied by an increase in the L/D. However, the use of a catapult reduces the initial fuel load without an accompanying increase in the L/D, because the aerodynamic parameters are almost the same between the two models. Therefore, calculating the fuel consumption according to the Breguet formula suggests that it cannot make a flight in the same range. For this reason, the Breguet formula is not suitable for calculating fuel economy improvement. Therefore, in this study, we instead employ an equation that can be used in a turbofan engine based on mass flow due to the limitation of predicting the fuel economy improvement caused by the use of the catapult with the Breguet equation. The mass flow relational equation according to the flow rate change under constant velocity motion conditions during cruising is as follows.

$$m = m_1 - \int_0^t \dot{m}_{f(cruise)} dt \quad (4)$$

Where m is the total mass of the aircraft, m_1 is the initial mass at the cruising altitude of the aircraft, and $\dot{m}_{f(cruise)}$ is the fuel consumption per second (kg/s) between cruises. At this time, if lift is solved for the weight of an aircraft, it is as follows.

$$L = m\,g = \left(m_1 - \int_0^t \dot{m}_{f(cruise)} dt\right) \cdot g \quad (5)$$

In addition, the relationship between the lift L and the thrust T is obtained and solved as follows.

$$\begin{aligned} & T_{Total} = D_{Total} \cdot T_{each} = \frac{T_{Total}}{n} \\ & T_{each} = \frac{D}{n} = \frac{D}{L \cdot n} \cdot L = \frac{1}{\left(\frac{L}{D}\right) \cdot n}\left(m_1 - \int_0^t \dot{m}_{f(cruise)} dt\right) \cdot g \\ & \left(\begin{aligned} \because TSFC_{cruise} \cdot T_{each} = \dot{m}_{f(cruise)} \\ \rightarrow T_{each} = \frac{\dot{m}_{f(cruise)}}{TSFC_{cruise}} \end{aligned}\right) \end{aligned} \quad (6)$$

Where TSFC refers to Thrust-Specific Fuel Consumption (TSFC), and if the equation is solved for $\dot{m}_{f(cruise)}$, it is as follows.

$$\dot{m}_{f(cruise)} = \frac{TSFC}{(L/D) \cdot n} \cdot g \cdot \left(m_1 - \int_0^t \dot{m}_{f(cruise)} dt\right) \quad (7)$$

Thus, both equations are differentiated and allocated to $\dot{m}_{f(cruise)}$,

$$\frac{d\dot{m}_{f(cruise)}}{dt} = -\frac{TSFC}{(L/D) \cdot n} \cdot g \cdot \dot{m}_{f(cruise)} \quad (8)$$

$$\frac{d\dot{m}_{f(cruise)}}{\dot{m}_{f(cruise)}} = -\frac{TSFC}{(L/D) \cdot n} \cdot g \cdot dt \quad (9)$$

Both sides are then integrated and arranged with an exponential function,

$$\ln \dot{m}_{f(cruise)} = -\frac{TSFC}{(L/D) \cdot n} \cdot g \cdot t + const. \quad (10)$$

$$\dot{m}_{f(cruise)} = C_1 \cdot \exp\left(-\frac{TSFC}{(L/D)\cdot n}\cdot g\cdot t\right) \tag{11}$$

Further, if the constant C_1 is obtained under the initial condition t=0,

$$\dot{m}_{f(cruise)} = C_1 \tag{12}$$

Then, substituting C_1 from the originally presented relational equation of $\dot{m}_{f(cruise)}$,

$$C_1 = \frac{TSFC}{(L/D)\cdot n}\cdot g\cdot m_1 \tag{13}$$

$$\therefore\ \dot{m}_{f(cruise)} = m_1\cdot\frac{TSFC}{(L/D)\cdot n}\cdot g \cdot \exp\left(-\frac{TSFC}{(L/D)\cdot n}\cdot g\cdot t\right) \tag{14}$$

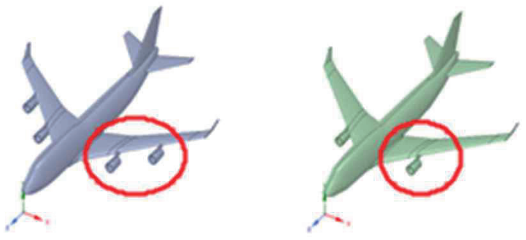
Since this equation is the fuel consumption per engine, multiplying it by the number of engines,

$$\therefore\ \dot{m}_{f(cruise)} = m_1\cdot\frac{TSFC}{L/D}\cdot g \cdot \exp\left(-\frac{TSFC}{(L/D)\cdot n}\cdot g\cdot t\right) \tag{15}$$

Here, $\dot{m}_{f(cruise)}$ is the mass flow of the fuel during cruise, m_1 is the fuel payload excluding the amount of fuel used during takeoff and climb, TSFC is the amount of fuel consumed per unit time per thrust, L/D is the lift ratio, n is the number of engines, g is the acceleration due to gravity, and t is the cruising time [4].

2.2 Lift to Drag Calculation

To calculate the fuel consumption of an aircraft, it is necessary to compare the aircraft L/D. Therefore, the L/D is derived through CFD, and two models are calculated: Model A with four engines and Model B with two of the four engines removed.



(A) (B)

Fig. 3 B747-400 Comparison Models

The B747-400 is modeled through reverse engineering based on its blueprint. The B747-400 is an aircraft with a supercritical bone airfoil, and six airfoils from BAC 463 to 474 are used in total, but the information on the airfoils is not available; it was therefore modeled using the BACXXX airfoil, a Boeing Commercial aircraft airfoil. Models A and B are shown in Fig. 3 [5-7].

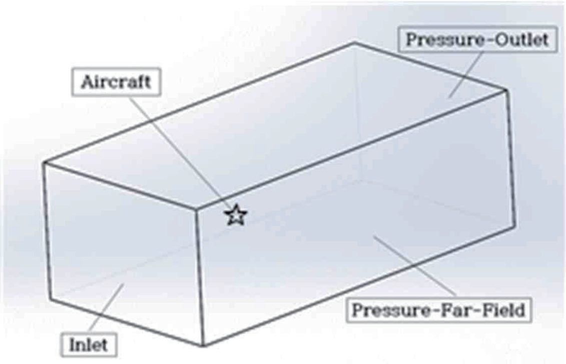


Fig. 4 B747-400 Analysis Domain

The boundary conditions of the flow field surrounding the aircraft are all pressure far fields, and the analysis domain is shown in Fig. 4. For the analysis grid of the model, 21.96 million meshes were generated in total with Poly-Hexcore using Ansys Fluent. The volume ratio of the aircraft to the total flow field is about 4,000,000:1.

The analysis uses the k-ω sst turbulence equation, and the ideal gas condition is used because the transonic velocity region is a compressible flow. The temperature and total pressure in compressible flow were respectively calculated according to Eq. (16) and Eq. (17) [8,9].

$$\frac{T_0}{T} = 1 + \left(\frac{\gamma-1}{2}\right)M^2 \tag{16}$$

where

$T_0 = Total\ temperature$
$T = Static\ temperature$
$\gamma = 1.4\ for\ air$
$M = Mach\ No. = 0.84$

$$\frac{p_0}{p} = \left[1 + \left(\frac{\gamma-1}{2}\right)M^2\right]^{\frac{\gamma}{\gamma-1}} \tag{17}$$

where

$p_0 = Total\ pressure$
$p = Static\ pressure$
$\gamma = 1.4\ for\ air$
$M = Mach\ No. = 0.84$

The angle of attack for a commercial aircraft during cruising is not constant because the computer automatically adjusts it according to the operating environment to maintain the set operating speed. The maximum L/D of an aircraft occurs between 4 and 5 degrees, but the Boeing literature states that the suitable angle of attack for the maximum cruising distance varies depending on the weight, speed, and altitude of the aircraft. Therefore, the angle of attack of the aircraft's maximum L/D was selected and analyzed [10].

2.3 Calculation Condition

The aircraft parameters were derived by referring to the literature. According to the literature, the maximum L/D at M0.7 is 15.6. However, for the latest b747-400 of the modern era, since there is little available information, the L/D was calculated based on the engine fuel consumption by altitude indicated in the manual, and it was derived from 35,000 ft to about 17.6. For aircraft operation, the route from Incheon to Manila was selected, and the specifications of the synthesized B747-400 are listed in Table 1 [11-14].

Table 1 Comparison of Models A and B

Parameter	Unit	
	Model A	Model B
Take-off Weight	308,442 kg	299,498 kg
Fuel Weight	31,752 kg	
Payload Weight	112,990 kg	
Engine Weight	4472 kg/ea	
L/D	17.6	19
Take-off Thrust of each Engine	276.23 kN	
Take-off Speed	290 km/h	
Cruise Speed	M0.84	
Cruise Altitude	35,000 ft	
Cruise Distance	2600 km	
Cruise Time	8360 sec	

The fuel amount calculation calculates the amount of fuel consumed take-off, climb, and cruising, and the amount of fuel during descending was derived by referring to the manual.

2.4 Thrust and TSFC at Flight

If two engines are removed during aircraft operation, the thrust needs to be doubled, and this increase in thrust is accompanied by a change in TSFC. Therefore, the thrust and TSFC for each section of Model A with four engines and Model B with two of the four engines removed were derived from the literature. According to the literature, the maximum efficiency of a turbofan engine occurs at a thrust higher than the cruising thrust. This is because, in the design of a turbofan engine, a thrust higher than the required cruising thrust is set as the design thrust, so the efficiency of each prop of the turbofan engine is the highest at the design thrust point; the graph showing this is presented in Fig. 5 [15].

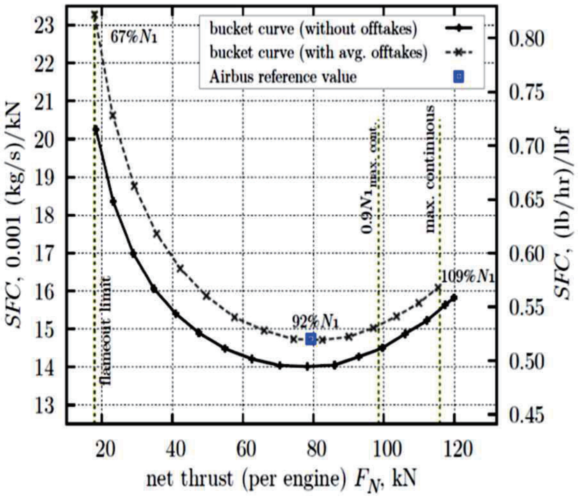


Fig. 5 SFC bucket curves at cruise design conditions (M = 0.85, 35000 ft, ISA) with and without the influence of average offtakes [16]

2.4.1 Thrust and TSFC at Take-off

During take-off, the aircraft accelerates using the maximum thrust, and the thrust and TSFC of each model are the same. In addition, for Model B, the catapult's fuel consumption needs to be additionally calculated because the catapult accelerates by obtaining insufficient thrust, but this was not considered here for simplification of the calculation. Thrust and TSFC during take-off are described in Table 2.

Table 2 Take-off Thrust and TSFC of Models A and B

	Model A	Model B
$T_{Take\ off}$	276.23 kN	
$TSFC_{\ Take\ off}$	28.3 g/kN·S	

2.4.2 Thrust and TSFC at Climb

Regarding the ascending thrust of Model B, it is necessary to double that of Model A, and the thrust for each model is derived from the literature and summarized in Table 3. Model B does not interfere with operation because it is within the range of the maximum engine thrust, even when using twice the thrust of Model A.

Table 3 Comparison of Climb Thrust of Models A and B

Altitude (1000 ft)	Model A - T_{climb} (kN)	Model B - T_{climb} (kN)
0-10	112	224
10-20	98	196

20-28	84	168
28-35	70	140

TSFC has different atmospheric conditions depending on altitude, so each altitude value must be considered. However, since it is difficult to reflect this, each required thrust and TSFC are derived by dividing the altitude section into an average value, and the fuel consumption when rising according to the corresponding value is calculated. These values are summarized in Table 4. In addition, when the required thrust varies due to a change in the fuel loading amount, the TSFC that matches the value is reflected and calculated.

Table 4 Comparison of Climb TSFC of Models A and B

Altitude (1000 ft)	Model A - $TSFC_{climb}$	Model B - $TSFC_{climb}$
0-10	15.6 g/kN·S	24.2 g/kN·S
10-20	15.1 g/kN·S	22.4 g/kN·S
20-28	14.81 g/kN·S	19.8 g/kN·S
28-35	14.92 g/kN·S	18.1 g/kN·S

2.4.3 Thrust and TSFC at Cruise

Table 5 shows the cruising thrust and TSFC derived from the literature. The engine used in the B747-400 has a design thrust of 80 KN, so the TSFC is lower than the actual cruising thrust of 44 KN. However, the calculation here proceeds without considering the fuel efficiency improvement of that part.

Table 5 Comparison of Climb Thrust of Models A and B

	Model A	Model B
T_{each}	44 kN	88 kN
$TSFC_{Cruise}$	16.7 g/kN·S	14.9 g/kN·S

Therefore, the increase in the required thrust in all sections satisfies the condition of the total thrust, so there is no problem in take-off, climb, and cruising, meaning that it can be operated appropriately. In addition, due to a lack of data, it is assumed that the amount of fuel consumption when descending is the same as stated in the manual.

3. Fuel Consumption Calculation

3.1 Model A case (Four-engine, L/D=17.6)

3.1.1 Fuel Consumption at Take-Off

Model A's fuel consumption during take-off is calculated using Eq. (18).

$$\dot{m}_{f(take-off)} = TSFC_{take-off} \cdot n \cdot T_{take-off} \tag{18}$$

To use this equation, the time required to reach the take-off speed must be obtained, and the corresponding value is derived using the acceleration formula.

$$a = \frac{T_{Take-off} \cdot n}{m_0} = \frac{276.23kN \cdot 4}{308{,}442kg} = 3.58\ m/s^2 \tag{19}$$

The time t until reaching take-off speed is

$$t = \frac{180mph}{3.58\,m/s^2} = \frac{80.43\,m/s^2}{3.58\,m/s^2} = 22.47s \tag{20}$$

Therefore, the amount of fuel consumption during take-off is calculated using Eq. (18), and $m_{f(take-off)}$ is 702 kg.

3.1.2 Fuel Consumption at Climb

The amount of fuel consumption during the climb is calculated using Eq. (21).

$$\dot{m}_{f(climb)} = TSFC_{climb} \cdot n \cdot T_{climb} \tag{21}$$

The required time was calculated based on the manual, and the fuel consumption according to the operating conditions is presented in Table 6.

Table 6 B747-400 Climb Table

Altitude (1000 ft)	Climb Time (min)	Amount of Fuel Consumption (kg)
0-10	5	2585
10-20	4	1632
20-28	4	1542
28-35	5	1224

3.1.3 Fuel Consumption at Cruise

The fuel consumption during cruising is the mass flow, which is calculated using Eq. (15), and the calculation is as follows.

$$\begin{aligned} m_{f(cruise)} = 300{,}757kg \cdot \frac{\frac{0.0167kg}{kN} \cdot s}{17.6} \cdot 9.8\,m/s^2 \cdot 8360s \\ \cdot exp\left(\frac{\frac{0.0167kg}{kN} \cdot s}{17.6 \cdot 4} \cdot 9.8\,m/s^2 \right. \\ \left. \cdot 8360s \right) \end{aligned} \tag{22}$$

The calculation result shows that $m_{f(cruise)}$ is 22,938 kg. According to the manual, the descending fuel consumption at 35,000 ft is 916 kg, so the total fuel consumption between aircraft operations is 31,539 kg.

3.2 Model B case (Two-engine, L/D=19)

3.2.1 Fuel Consumption at Take-off

Model B assumed that two engines were excluded from the initial weight and were accelerated by obtaining insufficient thrust with the assistance of the catapult, so in terms of acceleration, they received the same force as before. In the fuel consumption calculation, the effect of the catapult was excluded from consideration. The amount of fuel consumption during take-off was calculated using Eq. (18), and $m_{f(take-off)}$ was 341 kg.

3.2.2 Fuel Consumption at Climb

The amount of fuel consumption during the climb of Model B obtained using T is listed in Table 3, while that obtained using TSFC is presented in Table 4; these were both calculated through Eq. (21). The calculation results are listed in Table 7.

Table 7 Model B Climb Table

Altitude (1000 ft)	Climb Time (min)	Amount of Fuel Consumption (kg)
0-10	5	3252
10-20	4	2107
20-28	4	1596
28-35	4	1216

3.2.3 Fuel Consumption at Cruise

The fuel consumption during cruise in Model B is calculated using Eq. (15). The calculation is as follows.

$$m_{f(cruise)} = 290{,}986kg \cdot \frac{\frac{0.0149kg}{kN} \cdot s}{19} \cdot 9.8\,m/s^2 \cdot 8360s \cdot exp\left(\frac{\frac{0.0149kg}{kN} \cdot s}{19 \cdot 2} \cdot 9.8\,m/s^2 \cdot 8360s\right) \qquad (23)$$

The calculation result shows that $m_{f(cruise)}$ is 18,090 kg. The fuel consumption for each section is listed in Table 8.

Table 8 Initial Results of Fuel Consumption

Take-off	Climb	Cruise	Landing	Sum
341 kg	8,171 kg	18,090 kg	916 kg	27,518 kg

Iteration is calculated in the same way, and iterative calculation is performed while excluding the reduced fuel consumption from the prior calculation.

3.2.4 First Iteration Calculation

When the weight of fuel saved is subtracted from the initial weight and calculated after reducing the engine to two units, the fuel consumption for each section is listed in Table 9.

Table 9 First Iteration Results of Fuel Consumption

Take-off	Climb	Cruise	Landing	Sum
338 kg	8,056 kg	17,939 kg	916 kg	27,249 kg

3.2.5 Second Iteration Calculation

The weight of the fuel saved in the first iteration was subtracted from the initial weight of the first iteration and calculated. The fuel consumption for each section is presented in Table 10.

Table 10 Second Iteration Results of Fuel Consumption

Take-off	Climb	Cruise	Landing	Sum
338 kg	8,056 kg	17,898 kg	916 kg	27,208 kg

5. Result

The fuel consumptions of models A and B are compared in Table 11. When comparing the value in the actual manual and that of model A, the fuel consumption was well matched. It can also be seen that when two engines are removed, the fuel economy improves due to the weight reduction and an increase in L/D.

Table 11 Comparison Results of Fuel Consumption

	Take -off	Climb	Cruise	Landing	Sum	etc
Manual	-	6,983	23,852	916	31,751	-
Model A	702	6,983	22,938	916	31,539	≒14% decrease
Model B	338	8,056	17,898	916	27,208	

A graph illustrating the weight changes of models A and B according to flight time is shown in Fig. 6. In the case of Model B, it can be seen that the fuel consumption slope is different than that of Model A. Therefore, fuel economy is expected to improve as the distance increases.

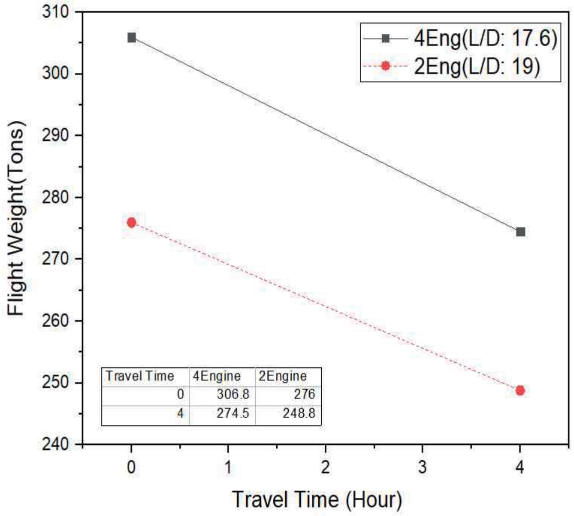


Fig. 6 Aircraft Weight Change with Operating Time

6. Conclusion

In this study, fuel consumption during aircraft operation with the assistance of a catapult was calculated using actual flight records and manuals. The CFD analysis results showed that when two of the four engines were removed, the reduction in shape drag by the engine increased, as did the maximum L/D. Regarding the fuel consumption, it was confirmed that a fuel-saving effect of about 14% was achieved by optimizing the thrust between flights through the take-off assistance. In the future, it is expected that more accurate fuel consumption calculations can be made by reflecting TSFC according to engine operating conditions and atmospheric conditions. In the future, we plan to compare fuel economy in long-distance flights and analyze the causes of drag reduction caused by engine removal.

Acknowledgements

This work was supported and grant funded by the Research Support Center at Dong Seoul University in 2019.

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