ANALYSIS OF OPTIONS TO REDUCE NO_x EMISSIONS OF AIRCRAFT ENGINES

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This article contains basic information about the principles of work and combustion process aviation jet engines, NOx formation, their impact s and effects, methods of measuring the amount of NO_x emissions and the possibilities to reduce emissions including the current used examples and solutions.

K e y w o r d s: emissions, combustion, combustion chamber, jet engines

1 INTRODUCTION

Along with the increasing number of carriers, airlines and especially with the growing number of the aircraft began to grow and produce emissions.

Emissions from aviation currently represent around 3% of total greenhouse gas emissions and their volume increases (from 1990 to 87%). There is a presumption that air emissions will increase over current levels by 2020, more than twice.

Despite the fact that aviation contributes to climate change, at least, it is important to resolve this situation and create opportunities to reduce emissions by all possible ways. One possible way is the solution to reducing emissions by changing the structure.

2 JET ENGINE WORK PRINCIPLE

Jet engine, works on the so-called „Brayton circulation". Its basis is at work of gas turbine open cycle. Fresh air enters the engine compressor which raises its temperature and pressure. This high pressure air then proceeds into the combustion chamber, where the mixture burns at a constant pressure. A gas of high temperature, passing through the turbine blades, which inflate at atmospheric pressure [1].

Brayton cycle is basis of jet engine work.

Jet engine work principle can be divided into four cycles similar to that of piston engines: air intake, compression, expansion and exhaust.

Work of jet engine begins by intake of air into the inlet tract and then, its compression by compressor. Then the air flows into the combustion chamber, where the fuel is added to it and this mixture is then ignited. The gases generated by combustion, escape from the combustion chamber and flows through the gas turbine blades, which drive it. Turbine is connected to the compressor by shaft, which drives the compressor and provides a new supply of compressed air into the combustion chambers.

The stages of jet engine work are performed by structural parts of jet engine: air inlet, compressor, combustion chamber, gas turbine, exhaust system [2].

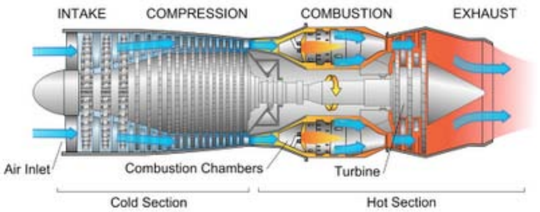

Figure 1. Parts of jet engine [12]

On the production of NO_x has the greatest impact combustion chamber (due to high combustion temperatures). Therefore, to reduce NO_x emissions consisting mainly used a variety of improvements and improved version of the combustion chambers.

3 JET ENGINE COMBUSTION PROCESS

The main task of the combustion chamber is to provide a constant mixture of fuel and air necessary to power the turbine. Combustion process must take place within a limited volume of the combustion chamber with minimal pressure drop. The combustion process is imposed strict requirements due to air and environmental pollution.

The second major task of the combustion chamber is to provide the right mixture of fuel and air for combustion. Perfect combustion of the mixture was achieved by observing the stechiometric air and fuel ratio, of approximately 15:1, what means burning a mixture of fifteen air units and one unit of fuel.

The air, which enters through the compressor into the combustion chamber, has the speed of about 150 $m.s^{-1}$ (about 500 $ft.s^{-1}$). Flame spread speed in jet engine is about 25-30 $m.s^{-1}$. The flame would be extinguished immediately if they were exposed to the flow rate of 150 $m.s^{-1}$, what means, that the basic condition of combustion in the combustion chamber, is:

$$v_h > v_{pr} ,$$

v_h - speed of flame spread $[m/s]$,

v_{pr} - speed of air flow into the combustion chamber $[m/s]$.

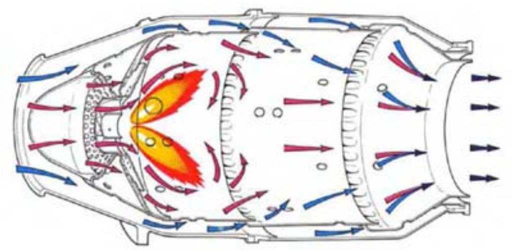

Figure 2. Combustion chamber work principle [11]

The basic condition is to reduce air speed, which ensures the front of the chamber. This section is designed as a diffuser, which slows the air flow and increases its static pressure. The speed reduction is not enough, the flow velocity has to be slower. So the air is divided into primary, secondary and tertiary:

Primary air - is about one-fifth of the total amount of air, entering into the combustion chamber. The primary air is mixed with fuel and directly involved in combustion. It is passing through the vortex generators to reduce its rate again, begins circulated, in which the axis of a suction vortex generators and ideal conditions for the flame that goes out.

Secondary air - is one fifth of the total amount of air passing through the combustion chamber. Secondary air is combined with the primary, creating a place with low flow velocity and flame stability and ensures its retention in place of fuel injection.

Temperature of the gases in the primary combustion exceeds 2000°C. It is necessary to reduce the temperature before it enters the gas turbine.

Tertiary air - the remaining two fifths of the total amount of air. Tertiary air flows directly into pennants, which cools the gas entering the turbine.

The basis of work of the combustion chamber is to provide the most efficient or the most ideal combustion, the ideal combustion occurs, when a hydrocarbon fuel molecules are mixed with just so much air that is consumed all the oxygen atoms, all hydrogen atoms create water vapour H_2O and all carbon atoms create carbon dioxide CO_2.

In fact, there is incomplete combustion, and at elevated temperatures are emitted into the atmosphere other molecules. In addition, at higher temperatures, is in fact oxidized only very small fraction of atmospheric nitrogen thereby consists of gases pollutants: nitric oxide (NO), nitrous oxide (N_2O) and nitrogen dioxide (NO_2) [10].

Polluting particles and gases produced by burning of aviation fuel:

Reactants:

1. Air $N_2 + O_2$
2. Fuel $C_nH_m + S$

Products:

$$CO_2 + H_2O + N_2 + O_2 + NO_x + UHC + CO + Soot + SO_x$$

Today's commercial aircrafts usually operate in that part of the atmosphere, which includes the upper troposphere and lower stratosphere, the tropopause. As the temperature is constant in the stratosphere, emissions can not get into the higher altitudes. Therefore, the emissions are maintained at its height a long time.

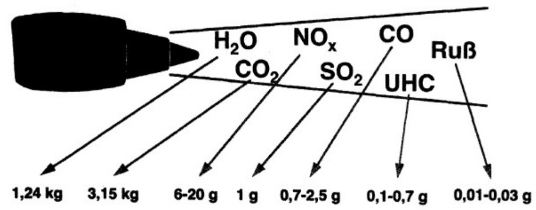

Figure 3. Quantity of emissions in g/kg of aviation fuel [11]

4 THE NO_x EMISSIONS FORMATION

Emissions of nitrogen oxides are formed by oxidation of nitrogen in fuel and oxygen in the air at a temperature higher than 600°C. At higher temperatures (above 1300°C), nitrogen oxides are formed directly from the air. First, there is NO, nitric oxide, which in turn, is oxidized by air oxygen to nitrogen dioxide NO_2. Effective oxidizing agent in this reaction is ozone. Short-wave ultraviolet radiation breaks down molecules of NO_2 to nitric oxide and oxygen.

It is generally known, that oxides of nitrogen resulting from nitrogen contained in the fuel and the combustion when exposed to high temperatures and pressures.

Emissions of NO_x contained in exhaust gases are composed of nitric oxide NO (about 90%of the total NO_x) and nitric oxide NO_2 (about 5% of the total NO_x), oxides of these are collectively known as NO_x. The remaining nitrogen oxides contained in exhaust gases are present only in small quantities and arise from the interaction of NO and NO_2 formation.

We divide three mechanisms of NO_x production:

- fuel,
- high-temperature,
- prompt.

Fuel NO: results from the nitrogen that is bound to the nitrogen compounds in solid and liquid fuels. Bound nitrogen content ranges from 0.1 to 2.0% by weight, depending on the type of fuel. Fuel NO is formed in the flame. The share of NO_x emissions at the fuel nitrogen is 35 to 80% of the total amount of NO_x emissions. NO_x formation is affected in this case, excess air, the share of volatile nitrogen and temperature.

High temperature NO: occurs due to high temperature oxidation of nitrogen contained in the combustion air. The speed of formation depends on temperature and reaction time at this temperature. The bulk begins to form around 120°C and under oxidizing conditions. Its number with increasing temperature increases exponentially.

Prompt NO: oxidation of molecular nitrogen on the edge of the flame in the presence of hydrocarbon radicals. NO formation is dependent on the excess air and temperature. Instantly there is NO greater at temperatures exceeding 2000°C.

NO_2 formation: NO_2 gas ratio is compared with the ratio of NO gas is low and usually only a few percent of the total exhaust gas NO_x. NO_2 occurs at lower temperatures than NO. NO_2 gas occurs by rapid cooling. The process of NO_2 emission is influenced by oxygen, O_2, sunlight intensity, reaction time and different phases of dirt in the air.

5 NO_x EMISSIONS IMPACTS

NO_x emissions have an impact on:

- atmosphere,
- environment,
- human health.

Impact on the atmosphere: emission of nitrogen oxides produces ozone O_3, which directly contributes to global warming. Ozone plays a very important role in the greenhouse effect, in the areas of the lower stratosphere and the middle and upper troposphere. The ozone layer in the stratosphere absorbs harmful ultraviolet radiation that would otherwise penetrate the Earth's surface. Ozone is a lapse in the atmosphere, and it is in a total volume of only a small amount. If all the ozone gathered on the surface, would have created a layer approximately 3 mm. Ozone is not regularly spaced, more is accumulated in the stratosphere. The area of highest incidence is around 25 km above the Earth's surface. The total amount of ozone in recent decades is significantly influenced by human activities, including production of aviation emissions.

The greenhouse effect is based on differences in absorption of different wavelengths of radiation by atmospheric gases. Solar radiation, which has the character of short-wave and the surface is absorbed, these gases pass. The earth radiates heat to the nature of long waves and generating greenhouse gases by reflecting back to the Earth's surface. The greenhouse effect is manifested on Earth since its inception. The atmosphere always contains some so-called greenhouse gases - carbon dioxide, methane, water vapour (greenhouse effect caused by all the molecules, which consist of more than 3 atoms, therefore it is not conducive to such as oxygen or nitrogen) [4].

Impact on the Environment: Nitrogen is a biogenic element, what means that it is a reasonable amount necessary for plant growth. It comes to land in the form of various fertilizers to support crop growth. On the other hand, the oxides of nitrogen as NO and NO_2, in higher concentrations, damage plants and cause them more susceptible to negative environmental influences such as frost or meld. Nitrogen dioxide and sulphur oxides are parts of the so-called acid rain, which have a negative impact on vegetation, buildings and further acidifying lakes and streams.
The reason is, that nitrogen oxides in the atmosphere gradually transferred to nitric acid, which reacts with dust particles and oxides such as magnesium and calcium or with ammonia to form particles that are removed from the atmosphere both by sedimentation and washing both rainfall. The amount of nitrogen that enters the atmospheric deposition of soil is no longer negligible, compared to the amount derived from fertilizer. Nitrate ions, which are then present in soils and waters, although has a positive effect on plant growth, but at higher concentrations can occur well as mortality and unwanted growth of aquatic plants [4].

Impact on human health: Nitrogen oxides can have a negative effect on human health, especially at higher concentrations, which are normally not present in the air. Inhalation of high concentrations of gas, or even of pure gases, however, leads to serious health problems and can even cause death. It is assumed that the oxides of nitrogen bound to aggravate the blood pigment and the transfer of oxygen from the lungs to the tissues. Some indications suggest that nitrogen oxides have a role in the development of cancer. Inhalation of high concentrations of nitrogen oxides irritates the respiratory systems [4].

Overall, based on summaries of the negative impact stated, that nitrogen oxides are substances with a wide range of negative impacts such as health and in particular the impact on the global ecosystem. It is therefore necessary to measure the amount and limit their production.

6 MEASUREMENT OF NO_x EMISSIONS

Measurement of emissions NO_x takes place in the regulation L16/II, by execution of chemiluminiscent method, which measures radiation produced by the reaction of NO and O_3. This method is not sensitive to NO_2, so samples must before measuring the total amount of NO_x; go through the converter where NO_2 emissions are converted to NO. Both concentrations as initial NO concentration and total concentration of NO_x must be recorded. The difference of these values must then be obtained from the measured concentration of NO_2.

The used apparatus must be fully equipped with all necessary components for controlling the flow, such as regulators, valves, flow meters. Materials in contact with the gas sample must be limited to proof of nitrogen oxides, such as stainless steel, glass and so on. Sample temperature must be accompanied by local pressure throughout the facility is maintained at values at which prevent water condensation.

The outlined service specification applies generally to the analyzer operating at full scale. Using partial scale errors can be significantly larger percentage deduction. The importance of such stature has to be weighed when preparing measurement. If it is necessary to better design, they must take appropriate action.

The levels of gaseous emissions of NO_x, if the measured and calculated in accordance with the procedures set out in regulation L16/II and transferred to the characteristic levels according to the procedures set out in regulation L16/II shall not exceed the prescribed levels specified regulations.

Based on the measured values, ICAO publishes certificate of emissions capability [5].

7 OPTIONS OF EMISSIONS REDUCTION

There are several options for emissions reduction:

- by improving the combustion process and working cycle of the engine,
- flight level change (lower flight level),
- use of alternative sources,
- improving the aerodynamics of the aircraft.

Improving combustion process and working cycle of the engine: Improved combustion process and working cycle of the engine allow emission reduction in the power train options. This method consists in reducing the emission index, improved combustion (reduce total emissions produced per kilogram of fuel) and change the engine cycle, resulting in lower fuel flow (there is a reduction in the amount of fuel consumed). A partial solution for global emissions reduce, is higher compression ratio of engine, resulting in more complete combustion and reducing fuel flow. This solution can be called a compromise, because the expense of reducing overall emissions will increase NO_x emissions, due to increased combustion temperature, leading to increased decomposition of nitrogen, and thus higher NO_x EI.

Improving the combustion process can reduce the amount of NO_x and CO_2 released into the atmosphere. However, change configurations or operating conditions of the combustion chamber reduces NO_x emissions, but increase the total amount of produced CO_2 and unburned hydrocarbons.

Flight level change: Advantages of flight in the lower flight level are twofold:

- reduce the formation of condensation trails,
- reduce the impact of other emissions.

Both benefits can be achieved by flight operations outside the sensitive tropopause.

In the case of jet engines, would reduce flight level (from 11 km to 9 km), reducing the impact of NO_x and H_2O production would decrease by 75%. However, this method would have increased the effects of CO_2 on the third.

Boeing study, these data support with the conclusion, that the aircraft would have to be designed to fly at lower altitudes in order to achieve a decrease in the quantity of produced emissions.

The use of alternative sources international air transport is due to burning of massive amounts of fuel for high load environment. Aircraft manufacturers are therefore trying to reduce consumption and emissions by using alternative sources. This is for example the use of electric, bio fuels and solar energy. For example, Boeing has already begun testing the use of bio fuels in aviation. The use of bio fuels in the future should reduce air pollution, but this method is fairly criticized. The main technical problem of bio fuels is that it freezes at high altitudes. According to experts, the maximum permissible limit for flying is 4500m.

Another alternative is to use solar energy. Reducing emissions must go across existing transport options and solar planes just waiting in the wings. Using solar power in practice is possible only for small sport aircraft. As time and technology can expect a wider use of solar energy source.

Improving the aerodynamics of the aircraft: Improving the aerodynamics of the aircraft reduces friction and the size of the required strength, resulting in lower fuel consumption and the amount of produced emissions.

The solution is to reduce friction as well, as lower travel speeds (below Mach number). However, this option must comply with other requirements of the job (years). With this method it is important to perceive the aircraft as a whole.

New technologies, such as methods to increase laminar flow and a reduction in induced resistance as possible in their ability to increase aerodynamic efficiency and reduce fuel consumption by aircraft.

8 CONSTRUCTIONAL OPTIONS FOR REDUCING NO_x EMISSIONS

Currently there are two possibilities for reducing NO_x emissions:

- by reducing the maximum gas temperature in the primary,
- by reducing the residence time of mixture in the combustion chamber.

In terms of aircraft engine environment is crucial to the combustion chamber. Emission reductions can be achieved by adapting existing or designing new, cleaner combustion chambers. The new combustion chambers must meet ICAO Annex 16.

Reduction of NO_x emissions produced by air sound manner is a difficult process. Currently offering several available technologies for reducing NO_x emissions:

Water cooling of primary zone: The basis of this technique is the injection of water into the primary zone of the combustion chamber. It is shown that this technique has significantly reduced emissions of nitrogen oxides (up to 80%).

Injection water temperature is significantly reduced, thereby slowing the rate of NO_x. Using this solution, although increased emissions of CO, but this increase was not unreasonable. It is not possible to use this technique to reduce emissions during the flight, because the flow of water needed to achieve significant emission reductions, is difficult to reconcile with the fuel flow. Using this method is also problematic in terms of engine life, power, logistics, economy and problems associated with the costs of using demineralised water. Because of these factors is the technique of ingestion of water for cooling in the primary zone of combustion chamber criticised and has negative evaluations.

Atomization of air and rapid mixing of fuel and air: Another method that was used to reduce NO_x emissions was the air atomization and rapid mixing of fuel with air flow in the primary zone of the combustion chamber. This approach is discussed and it also describes NASA F101 engine used in aircraft B-1, using this principle. In the case of F101, there is a shortened overall length of the combustion chamber of typical dimensions, due to better prepare the mixture of fuel and air. This method reduces the amount of emissions produced by the engine on the ground and in flight by 50%.

The biggest emission reduction can be achieved by developing new designs of combustion chambers:

The combustion chamber CF6-80C: was developed by GE Aircraft Engines, in order to minimize the amount of emissions produced by the combustion process, of the CF6engines.

Improved combustion chamber burns fuel more efficiently and cleaner, reducing hydrocarbon emissions by 12%, carbon monoxide emissions by 22% and emissions of nitrogen oxides (NO_x) by 49% compared to ICAO standards.

The aim of development of this combustion chamber is to reduce emissions, especially in lower altitudes [6].

The combustion chamber PW4000-100 TALON II: New features of the combustion chamber Talon II, by Pratt & Whitney, reduce emissions and maximize engine life.

The name TALON means „Technology for Advanced Low NO_x“. Using the combustion chamber TALON II was achieved not only reduce NO_x emissions, but also CO and HC emissions. TALON II reduces NO_x by 30%, compared with its predecessor, and TALON is an integral part of the PW6000 engine family.

TALON II contains combustion liners, which are designed to accommodate different cooling temperatures in the combustion chamber. Inserts cool and not cool the hot areas that might not be chilled. This means that less air is needed to cool the burning and more is available to produce the fuel mixture. There is a better level of emissions. More efficient cooling of the combustion chamber maximizes the life of TALON II.

TALON II maintains the combustion mixture, which provides stability and power required for safe operation. Reduces residence time of mixtures at high temperatures, which leads to a further reduction of NO_x emissions[7].

Dual-annular CFM56 combustion chamber: Development of dual-annular combustion chambers was launched in 1989 in response to growing demands to reduce air emissions and the introduction of carbon taxes in some countries. The first engine (CFM56-5B), equipped with a dual-annular combustion chamber entered to service in early 1995.

This new type of combustion chamber was developed by CFM International.

Its contribution lies in a significant reduction of NO_x production. In addition, improved fuel economy, reduce CO_2 emissions by up to 15%. Compared with the current requirements produces 50% less emissions.

These positive results are achieved by reducing of the flame temperature and residence time by increasing of air velocity in the combustion zone and reduced physical length of the combustion chamber.

Dual annular combustion chamber contains in addition to the outer chamber, the inner ring of fuel nozzles. At low power levels to use only the outer circle, which is designed for low flow rates and low air flow, to support the stable operation and complete combustion. At high power, are both functional areas, but most of the fuel and air are burned in an internal (main) circuit. It is limited by length of stay, because the rate of combustion through the vortex generators is more than twice higher than conventional combustion.

Although, the activity of dual-annular chambers focuses as much as possible to reduce NO_x emissions, what also solves the problem of CO_2 emissions. Significant improving the combustion efficiency brought about significant reductions in CO_2 emissions.[8]

The combustion chamber GEnx TAPS: new combustion chamber, from General Electric Company (GE), is a groundbreaking technology of combustion, which significantly reduces the emissions produced by aviation. It is the most economical and most environmentally friendly combustion chamber used in the present.

TAPS key success lies in mixing air and fuel before it is burnt in the chamber. Air flow is directed into the combustion chamber through two high-energy vortex generators adjacent to the fuel nozzles. This creates a more uniform and poorer fuel-air mixture, which burns at lower temperatures.

Lower temperatures in the combustion chamber produces 30% less NO_x emissions than predecessors of this combustion chamber. Emissions of GEnx engine is about 50% lower than the new state limits.

In addition, to reduce NO_x emissions, TAPS produces low levels of carbon monoxide and unburned hydrocarbons. It also has the potential to significantly reduce exhaust soot and related particles. Due to the low temperature of combustion, are components of the GEnx engine longevity. Motor has new design thanks to a lower specific fuel consumption by 15% compared with its predecessor [9].

9 CONCLUSION

This article is based on the thesis "Analysis of options to reduce NO_x emissions of aircraft engines." It is written by the author of this article under the direction of Ing. Marián Hocko, PhD.

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