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AIRCRAFT BRAKE TEMPERATURE FROM A SAFETY POINT OF VIEW

Summary. Safety is critical throughout all stages of aircraft operation, from air mission to ground operation. One of the most important airframe systems that influences the efficacy of ground safety is a wheel brake system. Aircraft ground speed deceleration requires the dissipation of kinetic energy, which depends on aircraft weight and speed. Significant levels of aircraft kinetic energy must be dissipated in the form of heat energy. The brakes of heavy aircraft are especially prone to overheating during landing and taxiing on the ground. The aim of this paper is to focus on the dangers caused by aircraft brakes when overheating and ways in which to eliminate brake overheating problems from a safety perspective.

Keywords: brake, temperature, overheating, aircraft safety, brake cooling

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1. INTRODUCTION

Wheels, tyres and brakes are critical to ensure safe and reliable aircraft ground operation. The primary purpose of aircraft wheel brakes is to decelerate and stop an aircraft by transforming the kinetic energy into heat energy via friction and dissipation of heat to the surroundings.

The secondary function of aircraft wheel brakes is to hold the aircraft stationary during the engine’s run-up and, in many cases, steer the aircraft during taxi.

Aircraft brakes are arranged in multiple disk pairs, which are commonly referred to as the brake heat sink. Two main methods of increasing aircraft friction or drag are applied:

- air friction: aerodynamic drag (airbrakes, spoilers, flaps, reverse thrusters, drag shuts etc.)
- ground friction: wheel brakes (aircraft to ground drag)

The weight and speed of an aircraft during landing and taxing determine how much energy the brake friction material absorbs.

Brake sizing is based on heating during a single landing and takes into account that ventilation has a limited effect, while neglecting the contribution of possible thrust reversal, flaps and spoilers. This means that a high part of the kinetic energy on landing will be converted into brake heating; the part of the brakes that is involved is often referred to as the heat sink. This event can be expressed by a simple formula of energy balance [1, 2]:

$$\frac{1}{2} m_{aircraft} V_G \rightarrow \begin{cases} \text{Aerodynamic drag} \\ C m_{heatsink} \Delta T \\ \text{Reversal thrust} \end{cases}$$

where m refers to mass, V_G refers to ground speed, C refers to a specific head of heat sink material and T refers to temperature.

Wide body and military aircraft brakes use multidisc of rotor and stator brakes (Fig. 1). Brake housings contain several pistons for applications of the normal force needed to develop the brake torque.

Fig. 1. Multidisc brake
Source: authors’ ABT Košice wheel and brake shop

The landing kinetic energy of modern aircraft equates to several million joules. The brakes of large commercial aircraft must be capable of absorbing up to 135 MJ of energy. This enormous energy, when absorbed by the brakes within 10-12 s after landing, imposes severe thermal gradients of thousands of degrees centigrade per cm^2 across the friction elements and brake bulk temperatures of 1,000°C or more [3].

Brake materials have additional requirements, such as resistance to corrosion, light weight, long life, low noise, stable friction, low wear rate, and acceptable cost versus performance. The design of the brakes affects heat flow, reliability, noise characteristics and ease of maintenance.

This energy conversion process produces very high energy fluxes at the multiple friction interfaces, resulting in high temperatures and stresses in the brake heat sink. The friction and wear characteristics of the friction materials used in aircraft brakes are influenced by internal factors (such as friction-material composition and heat sink mass) and external factors (such as the amount of kinetic energy absorbed by the brake, the surface velocity of the friction interfaces and aircraft deceleration requirements). Simply put, these factors control the temperature at the interface as well as the normal and tangential forces of the friction material.

Potential problems related to excessive brake energy are:

- brake overheating
- brake fire
- brake fade
- brake welding
- failure of brakes or associated components
- fuse plug melt

2. OVERHEATING OF BRAKES

During normal or emergency aircraft braking, the landing gear of the aircraft is highly stressed and therefore deserves special attention. Due to increased weight (Airbus A380 MTOW = 575 tonnes) and higher landing speed (Airbus A380 = 240-250 km/h) of modern aircraft, as well as the requirement of extreme braking for the shortest path (for the Airbus A380, it is 2000 ft = 609.6 m of runway), brakes overheating are a frequent phenomenon. It is therefore understandable that the overheating of the brakes constitutes a hazard. Overheated wheels and tyres pose a risk of possible explosion because tyre pressure will increase considerably.

When parking the aircraft, it is therefore recommended to cool overheated wheel brakes and tyres, as well as provide aircraft parking in isolated areas. Using water as the cooling medium is not recommended unless it is necessary to protect people in the vicinity of overheated wheels.

The ICAO recommendation is thus: too rapid cooling of a hot wheel, especially if localized, may cause explosive failure of the wheel. Water fog can be used, but intermittent application of short bursts of 5-10 s every 30 s is recommended. Dry chemicals have limited cooling capacity but are an effective extinguishing agent. Once the tyres are deflated, any extinguishing agent may be safely used as there is no further danger of explosion.

Thermal fuse plugs (Fig. 2) prevent the violent explosion of tyres when maximum temperatures are exceeded. Most wheels of jet aircraft have fusible plugs, which melt at specified temperatures (e.g., 177°C) and deflect the tyre before dangerous pressures are reached.

The maximum temperature of the wheel may not be achieved in the period up to 15 to 20 min when the aircraft exits the process of landing and taxiing. Most modern large aircraft have temperature sensors built into the landing gear.

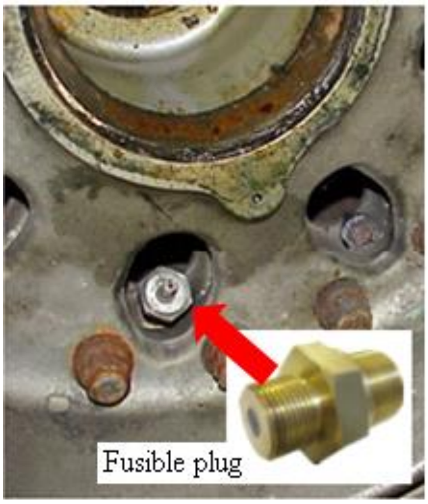

Fig. 2. Fusible plug on the wheel disc
Source: http://www.airliners.net/forum/viewtopic.php?t=594267

Taxing over a longer period at a higher speed may increase brake temperatures and cause subsequent fire in the wheel well at the stage of take-off for the aircraft. In this case, a flight with landing gear extended for a period of several seconds allows for rapid cooling of the brakes. Further, a flight with extended landing gear may continue until the warning light "OWH" turns off.

Boeing 747 has prescribed a speed limit during taxiing (maximum 10 km/h-1) before stopping, followed by landing gear checking and brake cooling.

During aircraft landing with intensive braking, in order to reduce landing run distance, certain types of anti-skid devices are damaged by overheating conditions.

The landing weight and interval before take-off play an important role in respect of the brake temperature, which has to be very carefully monitored in order to avoid exceeding the limit needed for energy stopping distance. Hot brakes can severely decrease braking performance in the event of a rejected take-off as well.

3. STRESS-STRAINS ANALYSIS OF BRAKE PLATES USING FINITE ELEMENT ANALYSIS

The aim of the numerical calculation was to compare two variants of brake pressure plates from the Airbus A320. Stress-strain analysis was focused on the identification of the most exposed areas, which could be the most probable areas of crack initialization (Fig. 3).

Fig. 3. Crack in the brake pressure plate
Source: author's ABT Košice wheel and brake shop

For this purpose, a nonlinear analysis was performed using the NX Nastran program, in which a simulated load was applied to the pressure plate's plastic deformation (Fig. 5). For the purpose of comparison, the load applied to both plates was identical.

Load conditions were established on the basis of input data and the formation of plate loading during braking.

Input data were received by the company that performed the analysis:

- material: steel size 17
- density: 7,928 kg/m^3
- modulus: E = 19,3140 MPa
- Poisson's ratio: μ = 0.3
- yield strength: Re = 280 MPa
- tensile strength: Rm = 520 MPa
- specific rate capacity: Cp = 0.49 kJ/kg°C
- pulse expansion: α = 13.10-6 m/mK
- coefficient of friction: f = 0.57
- contact force: Fn = 285 kN

Figure 4 depicts the course of the brake temperature increase and the brake temperature decrease (cooling).

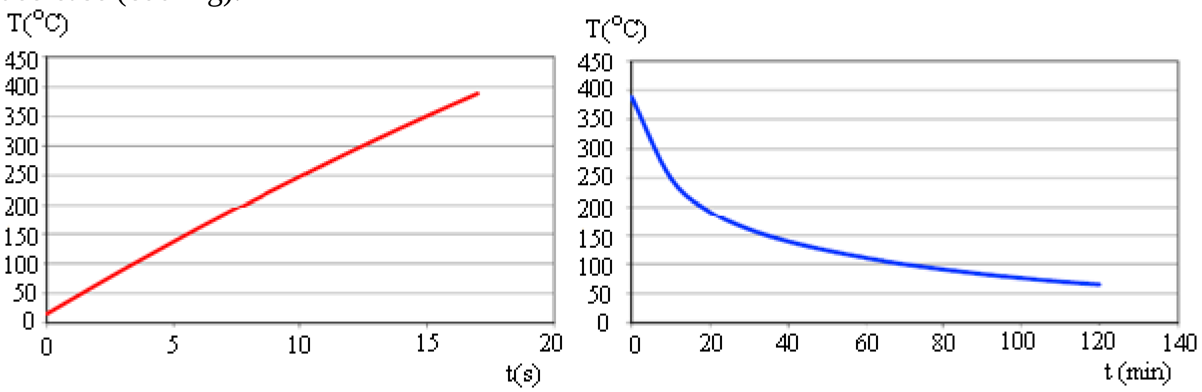

Fig. 4. Brake temperature increase and decrease
Source: authors

According to the analysis (based on a comparison of both models), it is evident that, under the same load conditions, there are more striking plastic deformations on Plate 1 than on Plate 2. A higher degree of plastic deformation of Plate 1 is linked to a higher probability of material deterioration under cyclic stress-strain conditions. Areas of material deterioration are mainly located at the end of dilatation slots, which are missing from Plate 2 (Fig. 5). From this point of view, the pressure from Plate 2 leads to better stress distribution around the potential stress concentrators (Fig. 5).

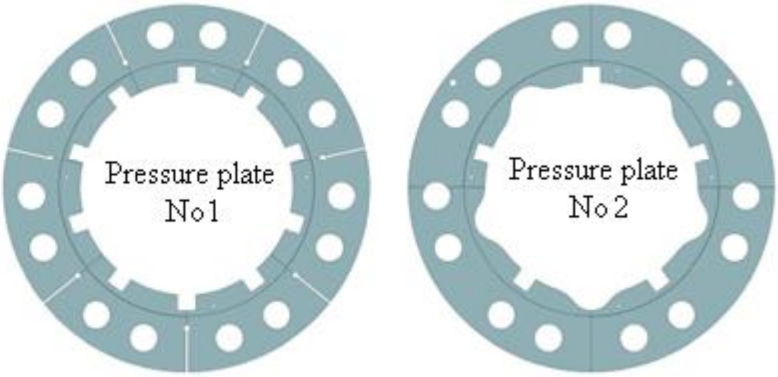

Fig. 5. Pressure plates from multidisc brakes

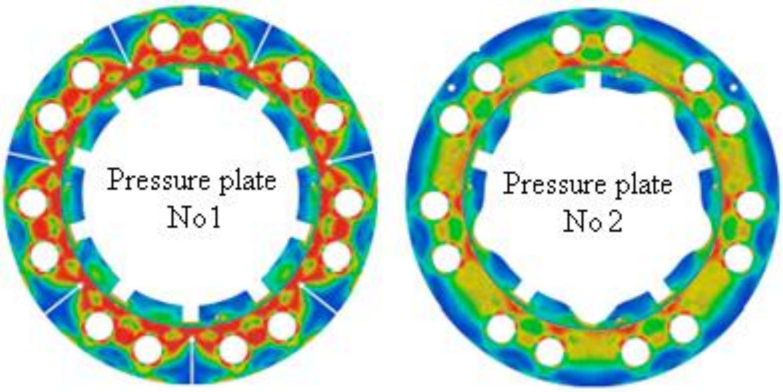

Fig. 6. Heat stress fields of pressure plates
Source: authors

4. BRAKE FIRE, FADE AND WELDING

When hydraulic fluid leaks onto the hot brake components, the fluid causes fire to break out. A mixture of the two types of hydraulic fluid lowers the temperature at which the fluid ignites, that is, below the flashpoint of pure MIL-H-83282 fluid.

An aircraft maintenance mechanic indicated that the two mixed hydraulic fluids, which are compatible, will reduce the fire resistance of the fluid.

Exxon HyJet IV-Aplus fire-resistant aviation hydraulic fluid has the following flammability:

- flash point = 174ºC
- fire point = 185ºC
- auto-ignition point = 427ºC

Another reason for a fire caused by overheated brakes is their proximity to the hydraulic and electrical system. In the case of Nigeria Airways flight 2120: “When the landing gear was retracted… burning rubber was brought into close proximity with hydraulic and electrical system components… causing the failure of both hydraulic and pressurization systems that led to structural damage and loss of control of the aircraft." The cause of the crash was found to be under-inflated tyres, which in turn caused overheated tyres to catch fire and the failure of the hydraulic systems.

Brakes can overheat for many reasons. A "dragging brake" can heat up on a long taxi and take-off run. When retracted into the wheel well, this can cause all sorts of problems. Taxiing too fast over long distances can cause these temperatures to become so hot that wheel well fires can develop after take-off. On large aircraft, brakes will reach their hottest point up to 15 min after landing.

Brake fade is a term used to describe the partial or total loss of braking power used in a vehicle brake system (Fig. 7). Brake fade occurs when the brake pad and the brake rotor no longer generate sufficient mutual friction to stop the vehicle at its preferred rate of deceleration. The brake pad in any brake system is designed to work at certain operating temperatures.

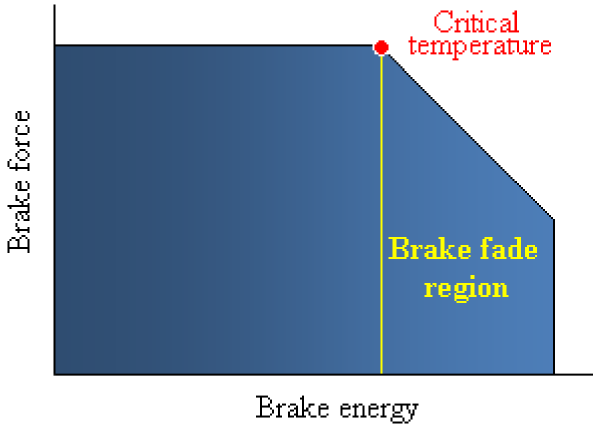

Fig. 7. Brake and brake fade region
Source: authors

New generations of passenger and freight aircraft are equipped with carbon brakes, as opposed to steel brakes found on relatively older aircraft. Carbon brakes have different characteristics and should be operated differently than steel brakes. When operating an aircraft equipped with steel brakes, the aircraft is required to use full reverse thrust and minimum braking to minimize the heat input into the brake assembly (rotors and stators). On long runways, braking can be delayed until the taxi speed is reached. This is especially convenient when the aircraft is not on the ground long enough for the brakes to cool. Carbon brakes have better properties in comparison to steel brakes: they are lighter and can absorb much more heat during a high-speed rejected take-off, as their stopping capability improves as they are warmed up [1, 2].

Maximum steel brake life can be achieved during taxi by using a large number of small and light brake applications, allowing some time for brake cooling between applications. Carbon brake wear is primarily dependent on the total number of brake applications: one firm brake application causes less wear than several light applications [4]. Carbon brakes are not susceptible to "welding".

5. TEMPERATURE SENSING AND MONITORING SYSTEM

The heating of aircraft wheels and tyres presents a potential explosion hazard, greatly increased when fire is present.

Modern passenger airliners are equipped with “BRAKE HOT” (Airbus) or “BRAKE OVHT” (Boeing) warnings for individual wheel brakes on the alert displays when the temperature of a brake rises above a predetermined level and turns off when all the brakes have cooled to a certain level.

The reason for the “BRAKE HOT/OVHT” warning is to eliminate the possibility of flames caused by hydraulic fluid (in the case of a leak of hydraulic fluid) when the landing gear is retracted into the wheel well. A warning will automatically start when the temperature reaches 400°C at the hottest part of the brake lining. The temperature of 400°C ensures the lowest limit of the auto-ignition of all hydraulic fluids used in the brake system. This mainly involves liquid Hyjet IV or IV+, whose temperature of auto-ignition (427°C) is specified under test conditions (under real conditions, the temperature of auto-ignition is considered to be much higher). The temperature indicated in the cockpit associated with the “BRAKE HOT” signal depends on the type and location of the temperature brake sensor. This temperature occurs in between 185°C and 260°C for carbon brakes. If the temperature is above this value, the alarm “BRAKE HOT” is signalled as “ON”, which means that take-off is not possible, as this may cause a fire in the landing gear wheel well in the event of hydraulic fluid leakage. Published ECAM procedures require a delay in take-off until the alarm goes to “OFF”. The alarm goes out when the temperature is 10°C below the temperature of triggering a warning, e.g., 290°C. Brake temperatures of each wheel are monitored in order to report brake temperature, warn the crew of brake overheat and indicate any malfunction, such as a dragging brake. A brake temperature monitoring system:

- prevents take-off with a hot brake
- prevent landing gear retraction with a hot brake
- monitors for residual braking due to a dragging brake

The “ON” warning appears at 300°C. To achieve an acceptable level of fire safety during a flight, Airbus uses a number of measures related to the “BRAKE HOT” signal. Some operators report that their activity is influenced by the time required for brake cooling, which is associated with signalling (e.g., 300°C).

6. BRAKES COOLING

Military and commercial aircraft are being designed for short turnaround times and short landings distances. These aircraft determinations reduce brake cooling times between usage and short landing distances, often resulting in the increase in brake applications. Therefore, brakes are sometimes applied while they are still hot and when the available kinetic energy in the brake is correspondingly reduced.

There are two ways of attacking the problem:

- make a thorough analysis of the expected operations and design the brake accordingly
- provide the brake with a cooling device

Analyses are provided by the brake manufacturer based on the mission profile data (temperature spectrum for a particular brake).

The role of any cooling medium is cooling, i.e., reducing the temperature of the object. This is done on the principle of the output of heat being by conduction, convection and radiation.

The most widely used principle of brake cooling is heat transfer by convection. Heat transfer by convection involves the movement of groups of molecules within fluids, such as liquids or gases (cooling medium) from one place to another.

Although water is a very effective coolant, it is technically and economically feasible in any airport. On the other hand, there are certain problems associated with the very intensive cooling effect of overheated brake parts, such as heat shock, which results in changes in the crystal structure of the materials. Moreover, in brake discs, cracks can result in brake life reduction. Less serious, but still an existing problem, is the fact that streams of water, if applied to the wheel, cause a washout of graphite lubricant materials from the wheel bearing. While air, like water, is a commonly used refrigerant, its cooling effect is significantly lower than that of water. In order to move heat from an air-cooled object, the air stream flow to the cooled object needs to be of a high speed. The higher the speed of the airflow acting on the cooled object, the higher the transport of thermal energy. In many operating manuals for propeller aircraft, the necessity to maintain the propeller speed to a proper regime is stated, in order to create cooling airflow to the wheels.

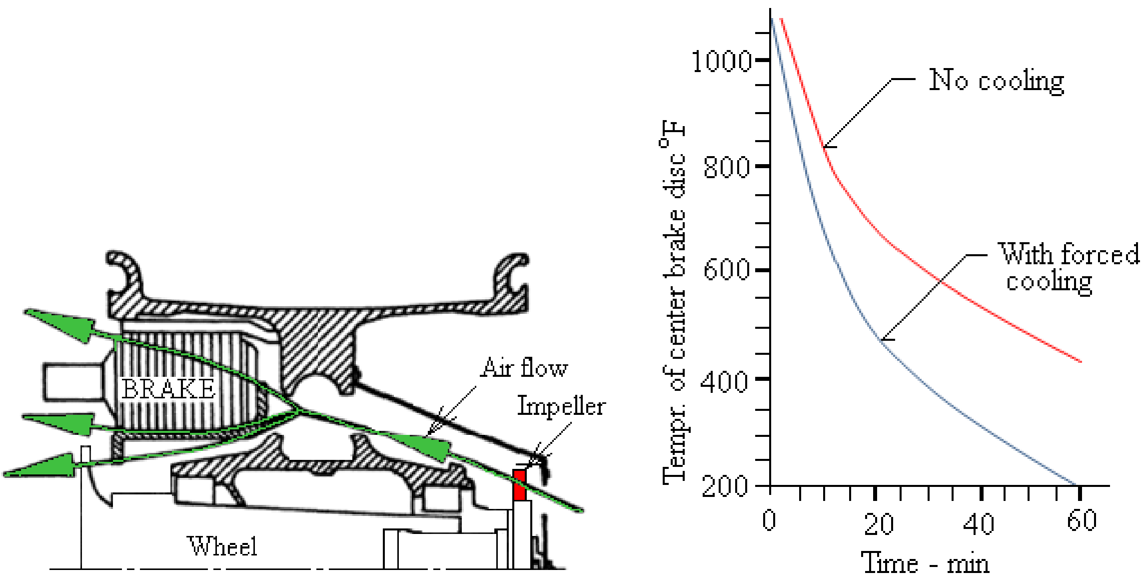

Fig. 9. Forced air brake cooling

Source: Norman S. Currey. 1988. *Aircraft Landing Gear Design: Principles and Practices*

Airbus A330 and A380 aircraft can be optionally supplied with integrated brake cooling fans. These fans are mounted on the brake assemblies of each brake and thus increase the weight of the aircraft.

Airbus wheel parameters include the following:

- A380 main wheel tyres that are 1.4 m high and 53 cm wide

- Maximum brake temperature for take-off for A320, A330 and A380 is 300°C. This limit prevents hydraulic fluid leakage, such that any hydraulic fluid that comes into contact with the brake units will not auto-ignite.

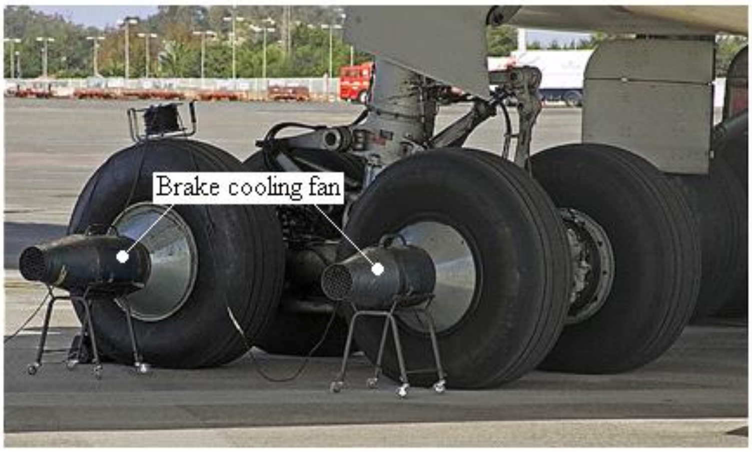

Fig. 8. Forced air brake cooling for aircraft
Source: http://www.airliners.net/forum/viewtopic.php?t=594267

7. CONCLUSION

Wheels and brakes are vital aircraft units, as well as being the most stressed parts of any aircraft. They are required to safely stop and operate the aircraft on the ground, often under appalling conditions, during both take-off and landing. In times of ground operation, they must withstand, absorb and safely dissipate the tremendous kinetic energy during the slowing-down of an airplane and bringing it to a safe stop.

Brake overheating is a potential hazard that can lead to brake fire, brake fade and brake welding and is considered as a serious problem for modern heavy aircraft, which is multiplied by short turnaround times and short landings distances for aircraft. Intensive brake applications, on the one hand, can save fuel and speed up aircraft turnarounds; on the other hand, the level of safety can be diminished, while the brake and wheel overhaul may be needed to be more frequent. From the analysis of the wheel and brake shops, it is clear that the intensive use of brakes, during aircraft operations, is less concerned with fuel safety and more about the considerable expense of brake and wheel overhaul.

For diagnosis purpose, non-invasive methods can be use. An interesting diagnostic methods are presented by the author in [5-16].

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