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Understanding and improving the brake cooling in disc brakes

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ABSTRACT:

Braking System is the need of every vehicle it involves mechanical friction between disc and pad which converts kinetic energy into heat energy. As soon as the brakes are applied, vehicle decelerates with a by-product of heat generation at the surfaces of disc and pad. Braking is an instant process, as long as the brakes are engaged the frictional heat generation continues and over a time it spreads within other components of braking system. This rise in temperature during braking process has an adverse effect on the braking performance. Generated heat must be dissipated immediately otherwise temperature at the interface rises with continuous braking. Currently brakes are cooled by the using natural air for cooling. However, this air cooling is not enough to carry away all the generated heat, hence heat accumulates and creates thermal problems such as brake wear, brake fade, cracking of disc, brake noise etc. The major problem associated with thermal behaviour of braking system are brake fade and brake wear, which directly contribute to the braking performance of braking system.

In this paper a literature review is carried out with an aim to present finite element analysis of effective Brake Cooling System for front brake of the ***Koenigsegg Agera RS***. Analyzing the disc rotor with different material and composition, and finding which material gives better result with actual driving conditions. By changing the ventilation type and adding drill hole for better heat dissipation. To aid the cooling of brakes, airflow from the front of the car is captured with ducts and channeled to the brakes through a flexible hose. This brake cooling hose is attached to an air guide (or brake duct) that is mounted to the wheel bearing carrier, and directs the air flow against the brakes. In most of the research thermal effect analysed by simulation are matching with the experimental results.

KEYWORDS: Disc, Pad, Brake, Fade, Wear, Thermal, Brake Colling

1 INTRODUCTION:

1.1 Background

Automotive brakes generate a considerable amount of heat during braking. This heat energy needs to be dissipated before next braking event, otherwise the temperature in the brake components will also increases, which leads to brake noise, brake wear, brake fade, cracking of disc etc.

In automobile, there are two types of brakes: disc brake and drum brake, as shown in figure.

Fig. 1: *Disc and Drum Brake*

Whenever brakes are applied, the vehicle starts decelerating. For achieving this deceleration there are several ways by which brakes can be applied such as hydraulic, mechanical, pneumatic, electromechanical, magnetic etc. but when it comes to actual stopping of vehicle, brake disc and pad friction. This friction between disc and pad creates the required friction to stop the vehicle and generates heat. Air cooling is insufficient in dissipating the entire heat therefore heat accumulates and creates issues such as brake noise, brake wear, brake fade, cracking of disc etc. Brake wear and brake fade are the main problems associated with thermal behaviour of braking system and directly impact the braking performance.

1.1.1 Company Presentation

Koenigsegg Automotive AB is a Swedish company that was started in 1994 and is a relatively small but prominent manufacturer of extreme and technologically advanced sports cars. The company is since 2003 based at the former air force wing F10 outside Ängelholm, Sweden.

Their most recent model, the Koenigsegg Agera RS, was launched at the Geneva motor show in March 2015. The Agera is planned to go into production during the second quarter of 2016 and it is the first Koenigsegg to utilize hybrid technology. The combined power of its internal combustion engine and its electric motors exceeds 1500 horsepower.

Fig 1.1: *Koenigsegg Agera RS (Koenigsegg Automotive AB, 2015)* (koenigsegg.com)

1.2 Objective

The objective of this project is to analysis, finite element analysis of effective brake cooling system for front brake of the ***Koenigsegg Agera RS***

1.2.1 Problem definition

The high performance of the Koenigsegg Agera RS requires efficient brakes. The average brake power during braking from 300 to 0 km/h, is about 1 MW. Track driving can result in excessively high brake temperatures, this may lead to friction material degradation, damage to the brake discs or brake fluid vaporisation. These failures modes can potentially result in partial or complete loss of braking and it can also lead to thermal damage to surrounding parts.

To increase air flow, the ambient air is captured with the help of duct and channelled to the brakes through a flexible hose. This brake cooling hose is attached to brake duct that is mounted to the wheel, and guides the air flow against the brakes.

Fig 1.2: *Agera Rs front brake*

2 Methods

2.1 Possible methods discussion

When finding the solution of a quantitative engineering problem, there are only three main methods – numerical methods, analytical methods and experimental methods. Many engineering problems can be solved with analytical method, this method is generally used at some stage in most projects. However, if it is necessary to make assumptions and simplifications to the problem to be able to calculate, it can normally provide valuable solutions.

Numerical simulations are run on computers which perform a huge number of calculations and give an approximate solution, which is very good if the calculation is detailed enough. The numerical approach makes it possible to study the subject in detail and monitor the properties of interest.

The experimental approach is often the most accurate since few assumptions and simplifications are needed. However, in some cases it may be difficult to accurately measure physical properties with good precision. In such cases it is hard to interpret the results and draw conclusions for further development. An experimental approach is usually more expensive and requires more resources, than analytical or numerical methods do.

2.2 Method used in this paper

This project involves heat dissipation rate and air flow around rotor disc, therefore the analytical approach is not applicable.

Whereas experimental approach would be possible but it requires a great number of prototypes, expensive test equipment and the cost to execution of many tests. And it would also be difficult to measure properties like temperature and velocity of air in detail. Hence experimental approach is not feasible for this project.

The numerical approach was chosen for this project because it is only feasible method available. This project only focusses on the *finite element analysis (FEA)* of disc brake.

3 Theoretical frameworks

3.1 Brake System

Disc brakes are mostly used in contemporary cars. The brake consists of a disc (rotor) which is coupled to the wheel and stationary brake caliper to squeeze pairs of pads against the disc to create friction. This action slows the rotation of shaft, either to reduce its rotational speed or to hold it stationary. The brakes on passenger cars are actuated with hydraulics using a brake fluid (different from other fluid) in order to avoid vaporization at high temperatures.

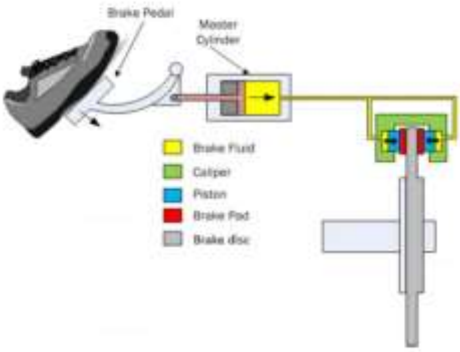


Fig 3.1: *Hydraulic disc brake system*

3.2 Brake energy

Mechanical brakes are transforming kinetic energy to heat energy and usually an insignificant amount of energy is also dissipated as sound. During a brake event, the brake caliper pistons press the brake pads against the surfaces of the rotating brake disc, resulting in friction between the pads and the disc. The friction force results in a counteracting (braking) torque due to the distance from the rotational centre. Heat is generated due to the friction in the sliding contact between the pads and the disc. The amount of energy converted to heat in the brakes during a braking event can be calculated using the formulas below.

The kinetic energy absorbed during the braking event can be calculated using formula

$$W_K = \frac{1}{2}\, m\, (v_0^2 - v_1^2)$$

Apart from the braking deceleration, the car is also decelerated by the aerodynamic drag force, formula

$$F_D = \frac{1}{2}\rho v^2 C_D A_f$$

There are also other losses, like rolling resistance, but these are negligible in this case. In order to get the work done by the drag force, it is multiplied by the distance in the form of vdt. And since velocity is not constant during the braking event, it must be defined as a function of time v(t). The work due to drag are obtained by integrating over the duration of the braking event.

$$W_D(t_0) = \int_0^t F_D\, v(t)\, \mathrm{d}t$$

The total energy (or work) that the mechanical brakes convert to mainly heat, can be calculated by subtracting the drag energy from the kinetic energy

$$W_{MB} = W_K - W_D$$

The amount of energy absorbed by the front brakes is proportional to the load on the front axle if the tyre friction coefficient is the same front and rear. With the assumption that the car is braked at the limit of lock up, that there is negligible aerodynamic downforce and that the aerodynamic drag force acts through the CG, the load proportion on the front axle can be calculated as below

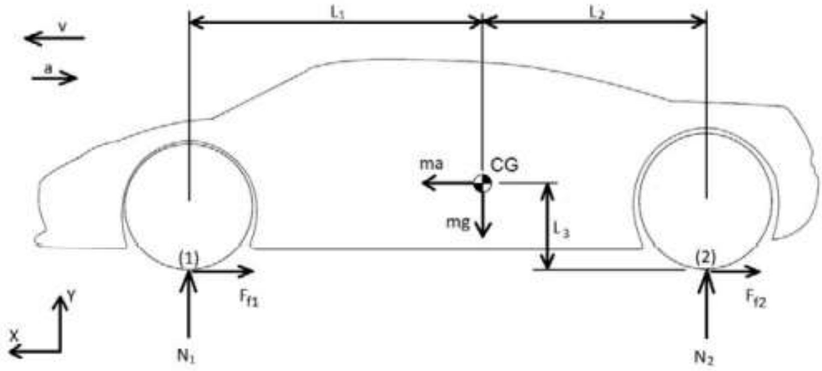


Fig 3.2: *Free body diagram of a braking car*

$$F_{f1} = \mu\, N_1$$

$$F_{f2} = \mu\, N_2$$

$$\sum F_Y = 0 = N_1 + N_2 - m\, g$$

$$\Rightarrow \; N_1 + N_2 = m\, g$$

The inertia force ma is acting in the opposite direction of the acceleration.

$$\sum F_X = 0 = m\, a - F_{f1} - F_{f2} = m\, a - \mu\,(N_1 + N_2)$$

$$= m\, a - \mu\, m\, g \Rightarrow a = \mu\, g$$

$$\sum M_{(2)} = 0 = N_1\,(L_1 + L_2) - m\, g\, L_2 - m\, a\, L_3$$

$$\Rightarrow N_1 = \frac{m\, g\,(L_1 + \mu\, L_3)}{(L_1 + L_2)}$$

Load proportion front axle

$$\frac{N_1}{m\, g} = \frac{L_2 + \mu\, L_3}{L_1 + L_2}$$

So, the amount of energy that is converted to heat in one front brake can be calculated with formula

$$W_{mbf} = \frac{1}{2}\, W_{mb}\, \frac{L_2 + \mu\, L_3}{L_1 + L_2}$$

3.3 Temperature calculation

If heat energy is added to a material, its temperature increases. The magnitude of the temperature raise depends on the material property *specific heat capacity (c)* and the mass of the object. The temperature change is calculated with the formula

$$\Delta T = \frac{Q}{c\,m}$$

Where, ΔT = Temperature change [K]

Q = Heat energy transferred [J]

c = Specific heat capacity $[\frac{J}{kg\,K}]$

m = mass [kg]

3.4 Modes of heat transfer

Heat transfer s generally occur in three ways – Conduction, Convection and Radiation. Let see how heat is dissipated in disc brake.

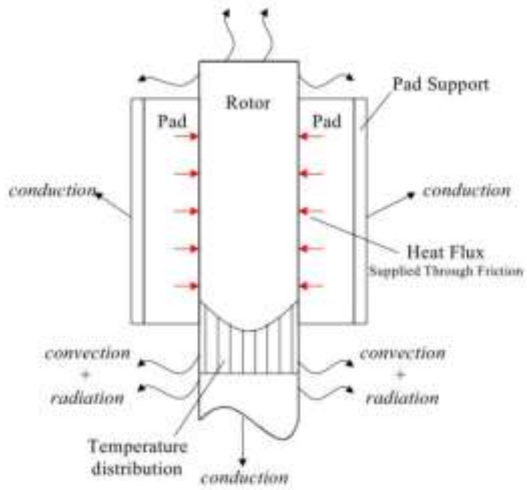


Fig 3.3 *Brake heat transfer modes*

3.4.1 Conduction

Conduction is the heat transfer process that takes place in solids and through physical contact between substances. This heat transfer process takes place at a molecular level, the heat causes the atoms to vibrate and collide with neighbouring atoms resulting in a domino effect that propagates throughout the substance. Solids and in particular metals are good heat conductors due to their closely packed atoms while gases are less conductive due to larger distances between molecules. The empirical formula for conduction also known as Fourier's Law

$$q = -k\,A\,\frac{\Delta T}{dx}$$

where

q = heat energy transferred per unit time [W]

k = thermal conductivity of the material $[\frac{W}{m\,K}]$

A = surface area [m^2]

ΔT = temperature difference over the material thickness. [K]

dx = thickness of the material [m]

3.4.2 Convection

Convection is the process by which heat is transferred by movement of a heated fluid such as air or water. If the fluid movement occurs due to density variations caused by local temperature gradients in the fluid, it is called *natural* or *free* convection. This is the way a heating element normally works in a room, the air close to the element is heated (through conduction) and then that hot air rises due to it being lighter than the surrounding air. This air motion helps to dissipate the heat in the room and continuously pass cold air over the heating element. If the fluid motion is caused by an external force such as wind or a fan it is called *forced* or *assisted convection.* Forced convection is in many applications used to increase the rate of heat exchange.

The empirical formula for convection, also known as Newton's Law of Cooling

$$q = h_c A \Delta T$$

where

q = heat energy transferred per unit time [W]

h_c = convective heat transfer coefficient $[\frac{W}{m^2\,K}]$

A = surface area [m^2]

ΔT = temperature difference between the surface and the bulk fluid [K]

3.4.3 Radiation

Radiation is a heat transfer mode that consists of electromagnetic waves (similar to light) that are emitted by the heated object. Unlike conduction and convection which needs a medium to transport the heat energy, radiation also occurs in vacuum and can travel vast distances. Air and many other gases are practically transparent for radiation, which means that little or no energy is absorbed by it. The electromagnetic waves emitted during normal cooling are in the so-called infrared spectrum, which is invisible for the human eye.

4 Component Description

4.1 Brake disc

Fig 4.1: *Front brakes, inside (left) and outside (right)*

The front brake discs are made of Carbon fibre-reinforced silicon carbide (C/SiC) and are 397 mm in diameter and has a thickness of 40 mm. Ventilation channels are provided in disc with same number of inlet and outside. The brake discs also have 90 cross drilled (axial) 3 mm holes that pass through the ventilation channels. The disc is mounted to its stainless centrepiece with a floating design, which allows the disc to move a small distance in the axial direction and expand radially while it is kept centred about the rotational axis, between the bolts holding the stainless centrepiece to the disc there are axial gaps approximately 2 mm wide

4.2 Brake Pads

The brake pads are of a conventional design, with a steel back plate to which the friction material is bonded. The friction material has low thermal conductivity compared to the brake disc material

Fig 4.2: *Front brake pad (hella.com)*

4.3 Brake Caliper

The brake calipers are of the fixed type with a total of six pistons, three on each side of the disc. The caliper body is milled from aluminium in two pieces which are bolted together. The pistons are made of a ceramic material in order to conduct less heat into the brake fluid.

Fig 4.3: *Front brake caliper (edrmagazine.eu)*

4.4 Wheel Rim

The Koenigsegg Agera RS wheel rims are made of carbon fibre to reduce the unsprang weight. They are 19 inch in diameter.

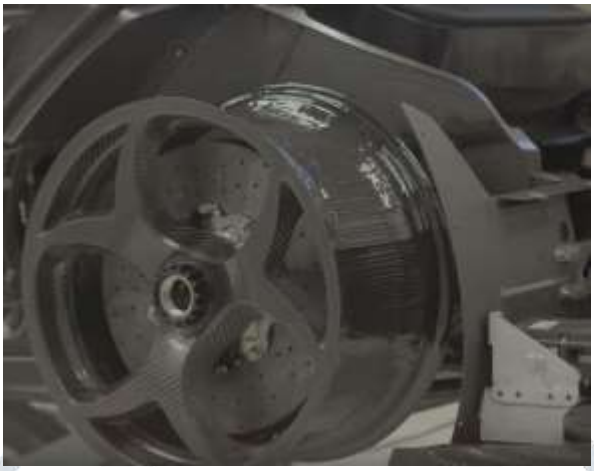


Fig 4.4: *Agera RS wheel rim (AutoEvolution)*

4.5 Brake Duct

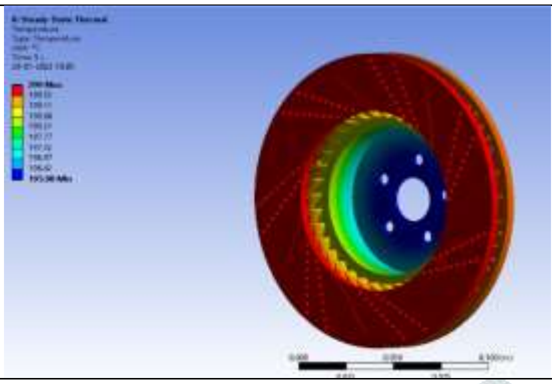
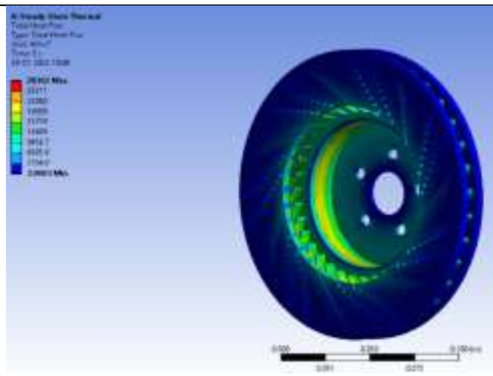
Brake ducts work by channelling air from a high-pressure source (usually the front surface of the car) to the brake rotor. The air introduced by the brake ducts is much cooler than the brakes, and the airflow continuously moves hot air away and allows the brakes to shed heat at a faster rate.

A cheap, light, and effective brake cooling system can be made by routing air from a high-pressure area on the body into the centre of each rotor. The goal is to increase the air flow rate through the brake rotor vanes, which will cool the rotors faster.

Fig 4.5: *Brake cooling duct* (koenigsegg.com)

5 Results

The majority of the results are presented in this section, a few more where simulated but are not included in this report.

<table>
<tr><td>Result 1</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Material (Tungsten)</td><td colspan="4">Because of its high melting point, tungsten may be used as brake rotor material
Melting point: 3,410 °C (6,152 °F)</td></tr>
<tr><td rowspan="2">Simulation Conditions</td><td>Maximum Temperature</td><td>Minimum Temperature</td><td>Total Heat Flux</td><td>Directional Flux</td></tr>
<tr><td>200°C</td><td>195.98°C</td><td>28362W/m² (max)
3.9603W/m² (min)</td><td>24687W/m² (max)
-10686W/m²(min)</td></tr>
<tr><td>Comment</td><td colspan="4">The results are not satisfactory, but with combination of Gray cast iron gives better results.</td></tr>
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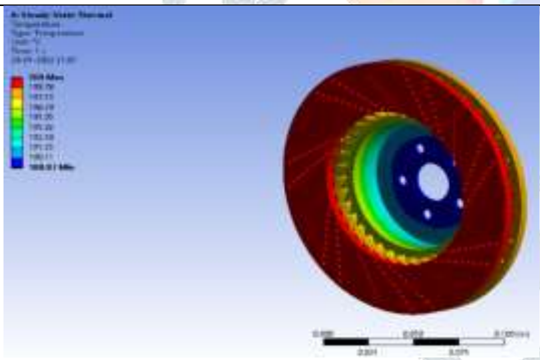
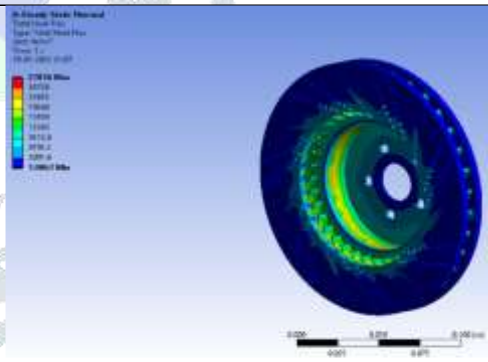
<tr><td>Result 2</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Material (Titanium)</td><td colspan="4">Titanium alloys are potentially good candidate brake rotor materials with the advantages of weight reduction and increased strength and corrosion resistance compared with cast iron.</td></tr>
<tr><td rowspan="2">Simulation Conditions</td><td>Maximum Temperature</td><td>Minimum Temperature</td><td>Total Heat Flux</td><td>Directional Flux</td></tr>
<tr><td>200°C</td><td>188.87°C</td><td>27816W/m² (max)
1.0867W/m² (min)</td><td>23781W/m²(max)
-10330w/m²(min)</td></tr>
<tr><td>Comment</td><td colspan="4">Results are better than tungsten</td></tr>
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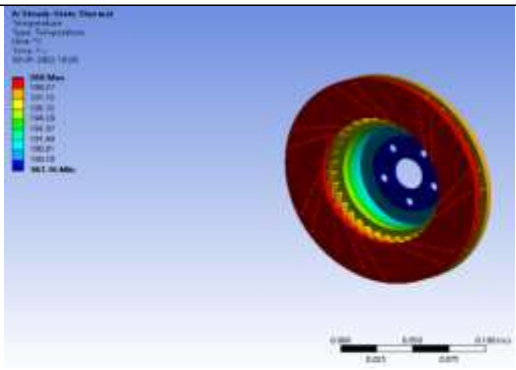
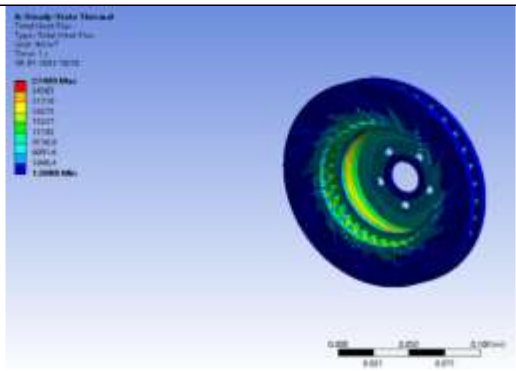
Result 3				
Material (Gray Cast Iron)	Gray iron is **the most widely used brake rotor material** in the industry owing to its superior thermal handling capacity, damping characteristics, and wear and cost advantages.			
Simulation Conditions	Maximum Temperature	Minimum Temperature	Total Heat Flux	Directional Flux
	200°C	187.16°C	27409W/m^2 (max) 1.0888W/m^2 (min)	23562W/m^2(max) -10250w/m^2(min)
Comment	Cast iron is very cheap to produce and **produces very good friction coefficients** but it is also fragile, it is not compatible with many modern pad materials			

6 Conclusion

It can be concluded that improving the cooling was more difficult than anticipated. Gray cast iron is very cheap to produce and **produces very good friction coefficients** but it is also fragile, it is not compatible with many modern pad materials.

Titanium alloys are potentially good candidate brake rotor materials with the advantages of **weight reduction** and increased strength and corrosion resistance compared with cast iron. Titanium may be used as rotor material but it is very costly, although titanium has good thermal properties, high strength to weight and corrosion resistance, this makes titanium an ideal material. But due to cost reasons we are unable to use it as brake rotor material.

Most of the modern cars, brake rotors are made from either cast iron or carbon ceramic materials. Tungsten carbide is a **dense, metal like substance, light gray with a bluish tinge**, that decomposes, rather than melts, at 2,600° C (4,700° F). It is prepared by heating powdered tungsten with carbon black in the presence of hydrogen at 1,400°–1,600° C (2,550°–2,900° F).

Tungsten carbide has high tendency of heat dissipation which makes it perfect for brake rotor material. Because so little of the rotor actually wears throughout its service life, it produces around 90 percent less brake dust and due to this life of disc increases around 30 percent. The tungsten carbide coating also allows the rotors to maintain cooler temperatures after repeated hard stops.

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