IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Numerical simulation of temperature field in a C/C composite multidisk brake during aircraft braking

To cite this article: E M Ramadan *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1172** 012004

Numerical simulation of temperature field in a C/C composite multidisk brake during aircraft braking

E M Ramadan[1,*], A E Hussien [1], A M Youssef [1], and T M Abd El-Badia [1]

[1] Military technical college, Mechanical Design and Production Department, Cairo, Egypt.

E-mail: eramadan@mtc.edu.eg

Abstract. This article presents a finite element method for simulating the heat production during stopping the aircraft. Thermal analysis and simulation in the finite element model are based on the theory of energy transformation and transportation. A commercial software COMSOL Multiphysics 5.5a is used for simulating the braking operation. The internal temperatures of the brake disks were obtained and the variation in temperatures between disks were discussed. Thermomechanical behaviour is studied to show the effect of thermal energy on the contact mechanics for the friction surfaces between the brake disks. Aircraft mass, initial velocity and deceleration rate are responsible for heat generation and consequently the maximum reached temperature during braking. The friction surfaces between disks were the main heat energy source where the heat was concentrating on these layers of friction surfaces. For the selected braking operation, the maximum reached temperature was 1020K. The finite element model was validated against historical data for a Boeing737-400 at constant deceleration for new disk brakes and for RTO brake energy.

1. Introduction

C/C composite material is used over worldwide as friction brake material due to its good advantages such as light weight, it can absorb high energy during braking, low coefficient of thermal expansion, resist thermal shock, stable friction properties, good wear characteristics in heavy conditions, work in very high temperature ranges, high strength and it has no melting point at atmospheric pressure [1-5]. Aircraft friction material absorbs millions of joules during braking as the kinetic energy is transformed into thermal energy at the friction surfaces between the rotor and stator disks.

The temperature distribution between the disks and the reached temperature can affect the contact between the disks and thus will affect the tribological behaviour of the brake disks [6-8]. Therefore, it is essential to investigate the effect of temperature variation on the brake disks under landing conditions for developing the friction material.

The issue has been investigated for many years by different researchers to find an accurate method for measuring the disks temperature during braking while taking into consideration contact and noncontact measurement between friction surfaces [9-11]. None of these researchers reached to a completely successful method for measuring the disks temperature at the contacting surfaces because of the sever landing conditions the brakes are working at such as high speed and heavy load.

The finite element simulating software gives a great opportunity to simulate the braking operation to study the friction behaviour under the temperature and contact effects[12]. Kennedy and ling[13] studied the effect of thermal deformation on the contact pressure between the multidisk brakes and achieved a numerical simulation for thermomechanical behaviour for the disk brakes. Choi and lee [6] used

IOP Conf. Series: Materials Science and Engineering 1172 (2021) 012004 doi:10.1088/1757-899X/1172/1/012004

ABAQUS finite element software for simulating an axisymmetric multidisk brake in aircraft including the thermoelastic contact problem and presenting the effect of temperature on the contact pressure between the contacting surfaces during braking.

However, in literature there are only a few investigations about the transient temperature field of C/C composite material during braking. For studying the transient temperature field changes and internal temperature gradient for C/C composite brake material a theoretical model was developed based on the phenomena of energy transformation during braking and transportation between disks. FEM was applied using the commercial software COMSOL 5.5a to solve the theoretical model.

2. Theoretical Analysis

2.1. Aircraft Brake Model

The aircraft brake assembly is shown in figure 1 introducing the brake system components. Aircraft brake is consisting of multiple disks stators, rotor disks, pressure plate and end plate. Number of pistons are used to produce pressure against the pressure plate in order to compress all the disks together to stop the aircraft. The torque plate or the end plate used as a constrain for the horizontal movement of the disks when pressure is applied. The torque plate and end plate are two stator disks but called with these names because of their function and position.

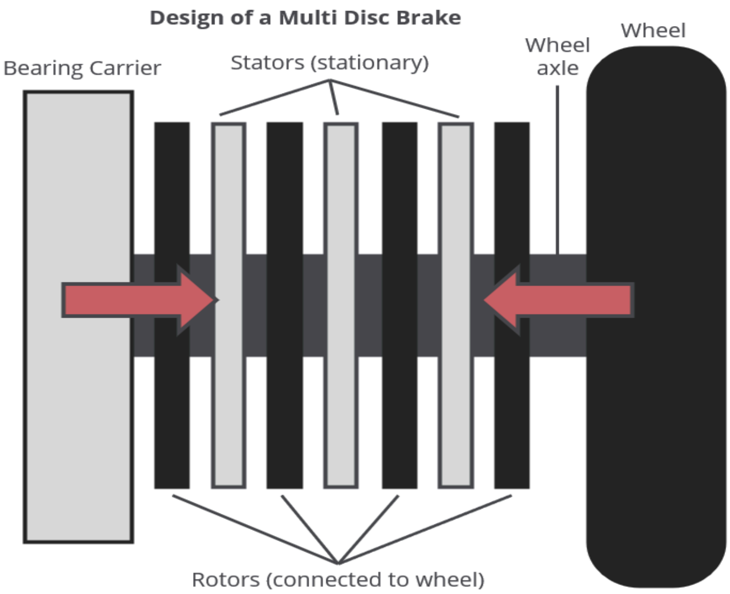

Figure 1. Aircraft brake assembly.

2.2. Theoretical Model

A 2D axisymmetric model is built to simulate the aircraft braking operation without scarifying the accuracy of the results as it reduce the computation time and reduce the data storage as well as shown in figure 2 . The aircraft brakes is consisting of seven disks three rotating disks which are connected with the rotating aircraft wheel and four stator disks which are consisting of the pressure plate and the end plate at the end of disks group. The disk brake dimensions are shown in table 1. The hydraulic pressure is uniformly distributed on the surface of the pressure plate as shown in figure 2. The displacement in z direction due to axial force applied on the pressure plate is constrained by the back plate. The pistons housing and torque tube has been neglected in the simulation model. There are six friction surfaces between the brake disks, which is used to produce friction to stop the aircraft, and these friction surfaces will be the heat source during braking.

During braking, disks temperature increase and transferred from disk to another depending on its thermal conductivity. In addition, disks dissipate heat by forced convection using air opposing the aircraft speed and heat radiation as heat diffuse from hot surfaces to the surroundings.
Depending on the law of energy transportation, the following differential equation is used to describe the heat flow between disks:

$$\rho\, c\, \frac{\partial T}{\partial t} + \nabla(-k\nabla T) = \rho\, c\, v.\Delta T \tag{1}$$

Where ρ the density of the disks material, c is the heat capacity of the disks material, k is the thermal conductivity of the disks material, v is the local velocity vector of the disks [7, 8, 14].

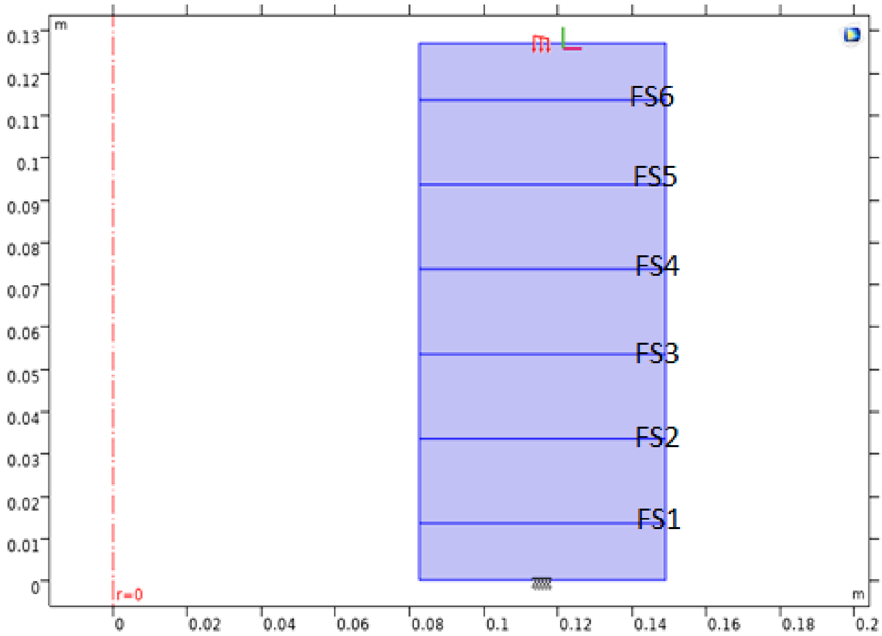

Figure 2. 2D axisymmetric aircraft brake model.

Table 1. Aircraft disk brake dimensions.

Disk type	Inner diameter (mm)	Outer diameter (mm)	Thickness (mm)
Stator and rotor disks	82.5	149	20
Back plate and end plate	82.5	149	13

2.3. Heat Power Generation

Heat power is generated due to the aircraft braking during landing with certain operating conditions; the speed of the aircraft was defined to decrease linearly with time in an explicit function. The heat power is obtained from the following equation:

$$p = -m\, v(t)\, a(t) \tag{2}$$

Where p is the heat power of one friction surface contact between two disks, v(t) is the velocity and a(t) is the deceleration of the aircraft, m represent the aircraft total mass [15-17].

2.4. Heat Transfer by Convection

Brake disks dissipate heat by forced convection during braking where the aircraft speed was assumed to be the same as the air speed facing the aircraft this will be the main reason for forced convection for the brake disks. Heat convection can be calculated from the following equation:

$$q = h\,(T_{ex} - T) \tag{3}$$

Where h is heat transfer coefficient, T_{ex} is the external disks temperature and T is the external air temperature [7, 8, 14]. Heat transfer coefficient is calculated from the following equation:

$$h = \frac{0.37\,k_{air}}{l}\,Re^{0.8}\,Pr^{0.33}$$

$$h = \frac{0.37\,k_{air}}{l}\left(\frac{\rho_{air}\,l\,v}{\eta_{air}}\right)^{0.8}\left(\frac{c_{air}\,\eta_{air}}{k_{air}}\right)^{0.33} \tag{4}$$

Where η_{air} is the air viscosity equals to 1.8e^{-5} N.S/m, l is the disk's diameter, $\rho_{air}$is the density of air; kair represents thermal conductivity of air; cair is specific heat capacity of air [7, 8, 14].

2.5. Heat transfer by radiation

The brake disks also dissipate heat by radiation to the surrounding air and can be calculated from the following equation:

$$q = \varepsilon\,\sigma\,(T_{sur}^4 - T^4) \tag{5}$$

Where ε is the emissivity, σ is the Stephan Boltzmann constant and T_{sur},T are temperature of the disks and surrounding [7, 8, 14].

3. Validation of Theoretical Model

The current model was validated against the results from Nihad et al. [18]. This paper is discussing modeling and computation of maximum braking speed of aircraft, brakes heat capacity and braking forces.

Nihad et al. build a model to indicate heat transfer and maximum temperature during braking conditions (landing and RTO) depending on historical data for Boeing737-400 series, which has the following data: The 737-400 aircraft has two main landing gears with four braked wheels. Every single wheel on axle is carrying five stators and four rotors with eight frictional contact surfaces.

Boeing 737-400 aircraft weight 65 tons to 68 tons and it has initial braking speeds 150 Knots, 160 knots and 170 knots, the aircraft initial temperature of disk brake is 400^{o}K and the surrounding temperature is 300 ^{o}K. The disks initial high temperature is because of taxi out braking operation.

Steel alloys material is used for braking operation for the Boeing 737-400 and it was used for the model results and validations. Disk brake dimensions and steel alloy material property are shown in table 2.

In order to validate the model, Boeing 737-400 RTO condition and normal landing conditions have been simulated in the 2D axisymmetric model by using COMSOL Multiphysics software to compare the model results against the historical data for the aircraft.

Table 2. Boeing737-400 steel alloy brake material properties and disk dimensions [18].

Property	Rotor and stator

Density (kg/m^3)	7780
Heat capacity C_p (J/kgK)	480
Thermal conductivity K (W/mK)	50
Disk outer radius (m)	0.25
Disk inner radius (m)	0.1443
Disk effective radius (m)	0.197
Disk thickness (m)	30
Wheel radius (m)	1.27

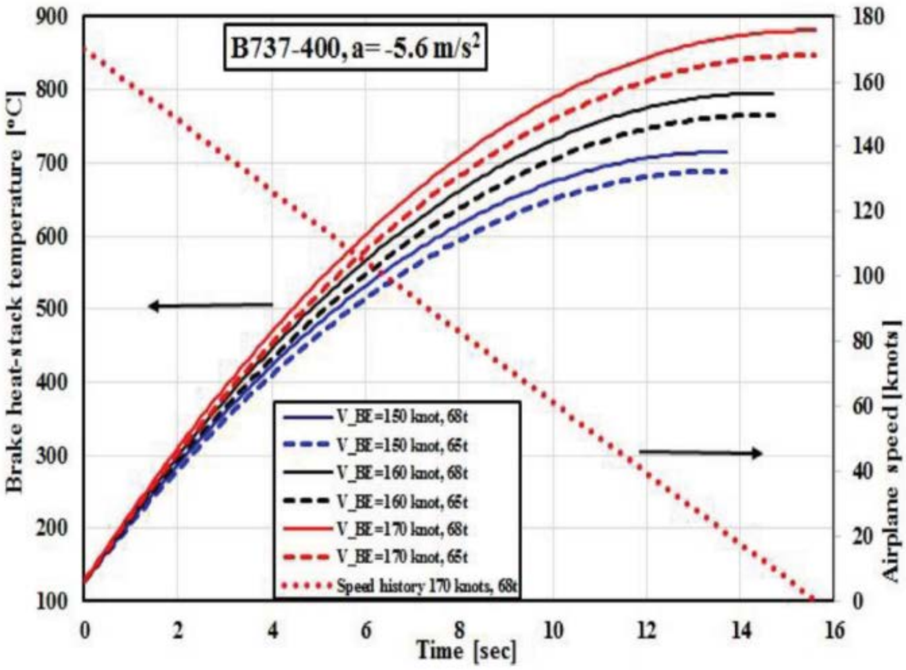

Figure 3. Temperature and speed histories for a Boeing737-400 at constant deceleration for new disk brakes and for RTO brake energy [18].

From the historical data for the selected aircraft, the RTO case has the following braking conditions initial speed 170knots, deceleration rate of 5.6 m/s^2 and 68 tons weight stopping at 15.76 sec where the disk peak temperature was 875°C. The model results showed that the maximum reached temperature was 842°c during the braking operation with error percentage 4.1% as shown in figure 4.

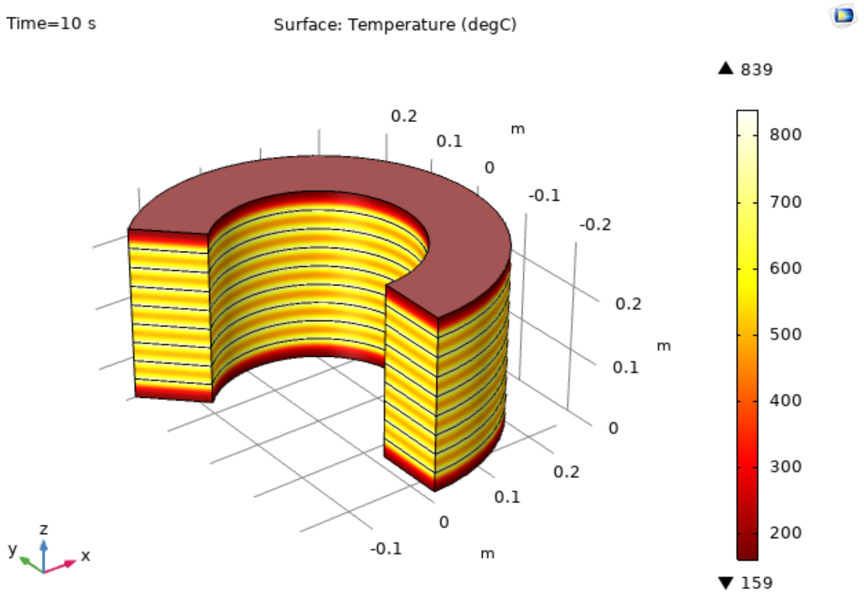

Figure 4. 3D temperature gradient for disk brakes during braking from v=170knots.

For further validating the model, another selected case from the historical data was simulated with weight of 65 tons, speed of 150 knots and deceleration rate of -5.6 m/s^2 stopping at t=13.77sec. The results showed that the maximum reached temperature was 710^{o}c, which is in agreement with temperature history of the Boeing aircraft 737-400 with error margin of 1.2% as shown in figure 5.

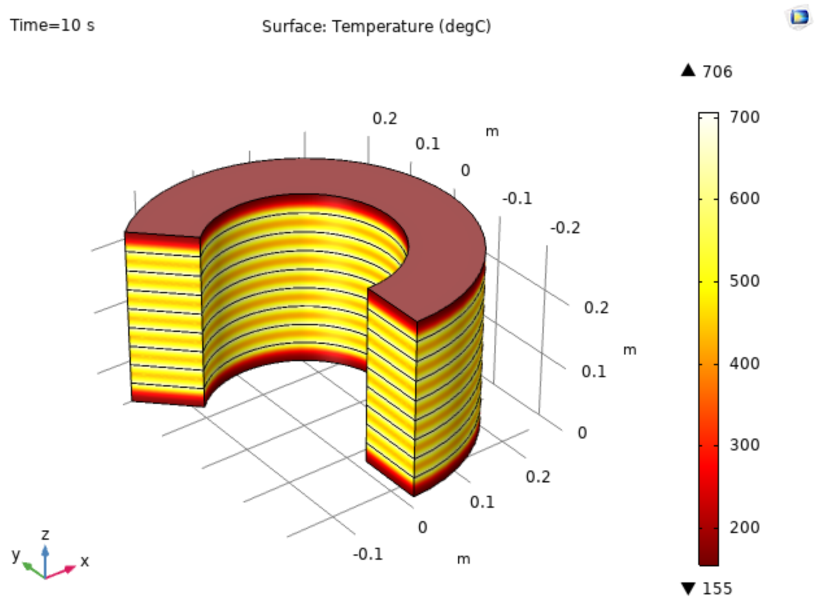

Figure 5. 3D temperature for disk brakes during braking for v=150knots.

4. Case study

C/C composite aircraft brake material is used in this model to simulate the aircraft braking operation with the following properties in table 3 [6]:

Table 3. C/C composite material properties.

Material property	Rotor and stator
Density, (kg/m^3)	1800
Modulus of elasticity, E_r (GPa)	50.9
Modulus of elasticity, E_z (GPa)	5.89
Poisons ratio, $\upsilon_{r\Theta}$	0.3
Poisons ratio, υ_{rz}	0.33
Shear modulus, G_{rz} (GPa)	2.46
Thermal conductivity, k_r (W/mK)	50
Thermal conductivity, k_z (W/mK)	10
Heat capacity, c_p (J/kgK)	1420
Thermal expansion, α_r (10^{-6}/K)	0.31
Thermal expansion, α_z (10^{-6}/K)	0.29

The air used for dissipating heat by forced convection has the following properties in table 4 [7]:

Table 4. Air thermal properties.

Air property	Value
Density, (kg/m^3)	1.177
Thermal conductivity, k (W/mK)	0.026
Heat capacity, c_p (J/kgK)	1.1

An aircraft with the following landing conditions as shown in table 5 is simulated in the model:

Table 5. Aircraft landing conditions.

Parameter	Value	Definition
m_plan	9000[kg]	Aircraft mass
r_wheel	0.352[m]	Wheel radius
v0	260[km/h]	Initial aircraft touch down speed
a0	-3.611[m/s^2]	Initial vehicle acceleration
T_air	300[K]	Temperature, air
t_brake_start	1[s]	Braking time (start)
t_brake_end	21[s]	Braking time (end)
P	0.7[MPa]	Braking pressure
mu	0.32	Friction coefficient

Aircraft landing speed is assumed to decrease linearly with time during braking as shown in figure 6. Aircraft deceleration for stopping the aircraft is assumed to be constant and is defined in analytic function as a constant value during the whole braking operation as shown in figure 7.

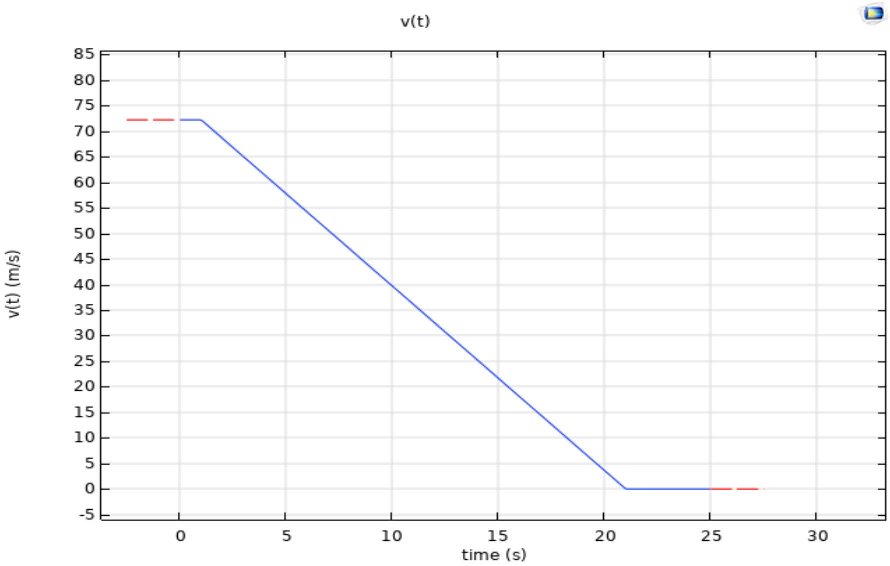

Figure 6. Aircraft velocity during braking.

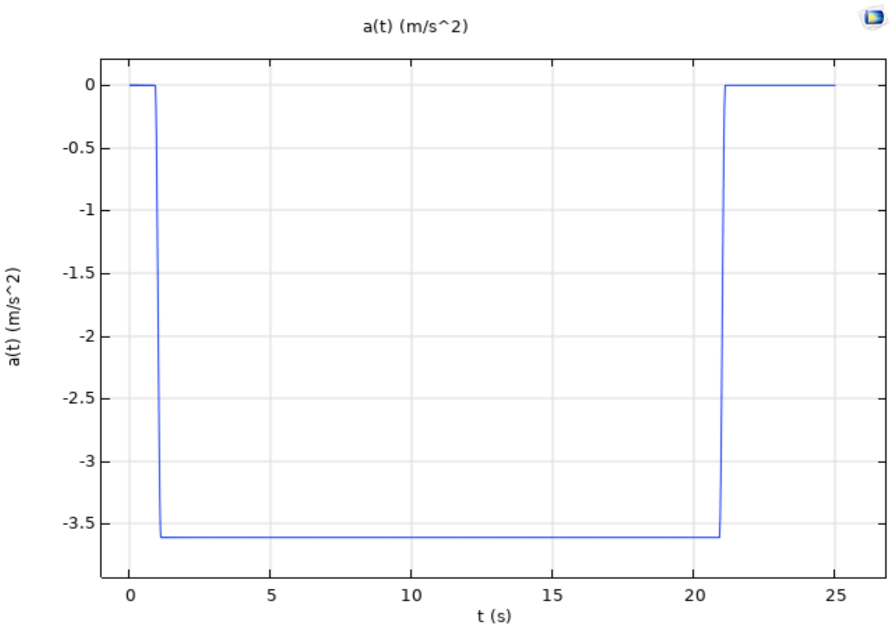

Figure 7. Aircraft deceleration during braking.

Mesh element size and number of elements has a significance effect on the accuracy of the results. Increasing the number of elements and reducing its size to certain size as fine or extra fine will give more accurate results, but also, it will increase time of computation and storage.

The model started as 2D axisymmetric model, mesh was build in free triangular elements by increasing the number of elements at the contact surfaces where the model results for contact pressure, and heat transfer is most relevant as shown in figure 8.

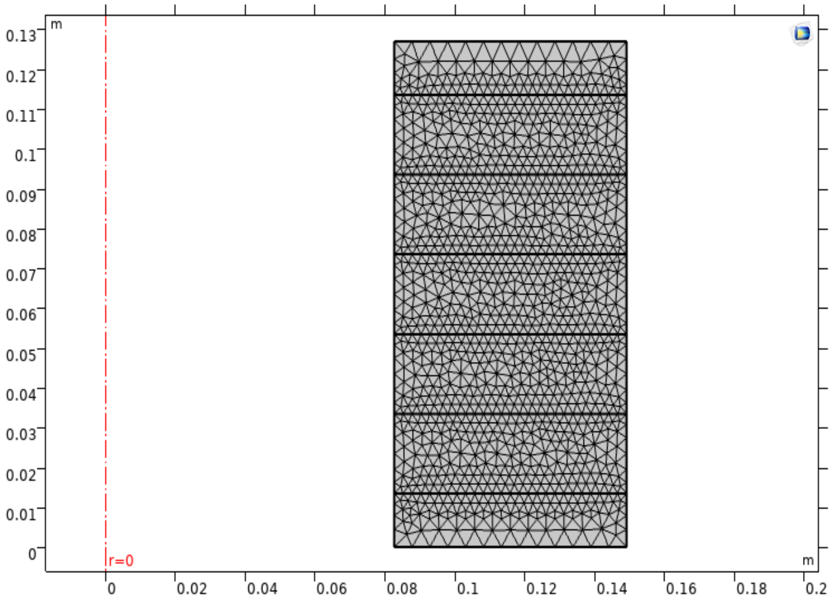

Figure 8. 2D axisymmetric model mesh build.

5. Results and Discussion

During braking, the kinetic energy is transferred into thermal energy. Using 2D axisymmetric model the temperature field simulation for braking operation was achieved. The highest temperature reached during braking at t=20sec was 1020 ºK.

As shown in figure 9 at t=1sec the friction surfaces start producing friction between disks to stop the aircraft as the friction surfaces are the main sources for heat generation, this heat will start to dissipate and transport to the other disks and to the surrounding air.

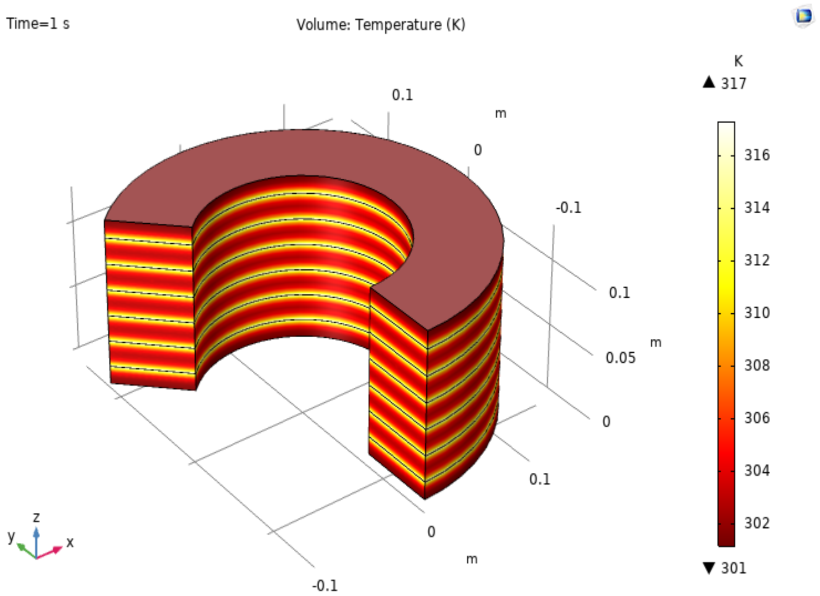

Figure 9. Disk brakes temperature while start braking at t=1sec.

Figure 10 shows how heat generation starts to propagate through the disks group as temperature increase with time during braking. It can be shown that the pressure plate and the end plate have lower temperature 374ºk than the other brake disks, as these disks are the most affected surfaces by air forced convection. Depending on the thermal conductivity property of the friction material heat will start to propagate through the thickness of the disk brake and then it will be dissipated to the surrounding air.

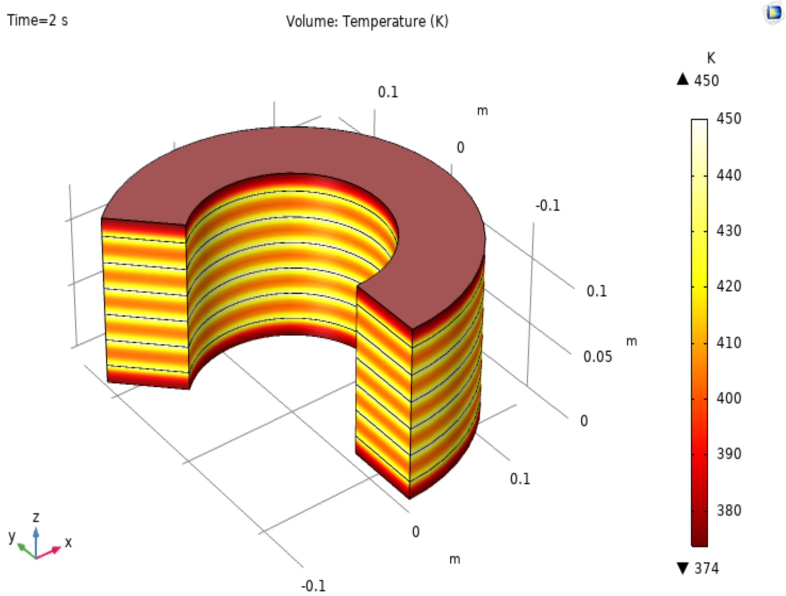

Figure 10. Disk brakes temperature during braking at t= 2sec.

Figure 11 presents the highest temperature the disks will reach in 3D and the hottest areas in the whole disks. The middle rotor disk (rotor disk that have fs3 and fs4) was found to have the highest temperature. This result explains that the temperature effect on the material thermal deformation and this affect the contact pressure between disks and the wear rate of the C/C composite disks. It can be deduced that the thermal effect has a clear effect on the tribological behaviour for C/C composite. It can be shown that minimum and maximum temperatures for the brake disks after braking are from 956K to 1033K at the end of braking the brakes thermal temperature will decrease and cooling starts.

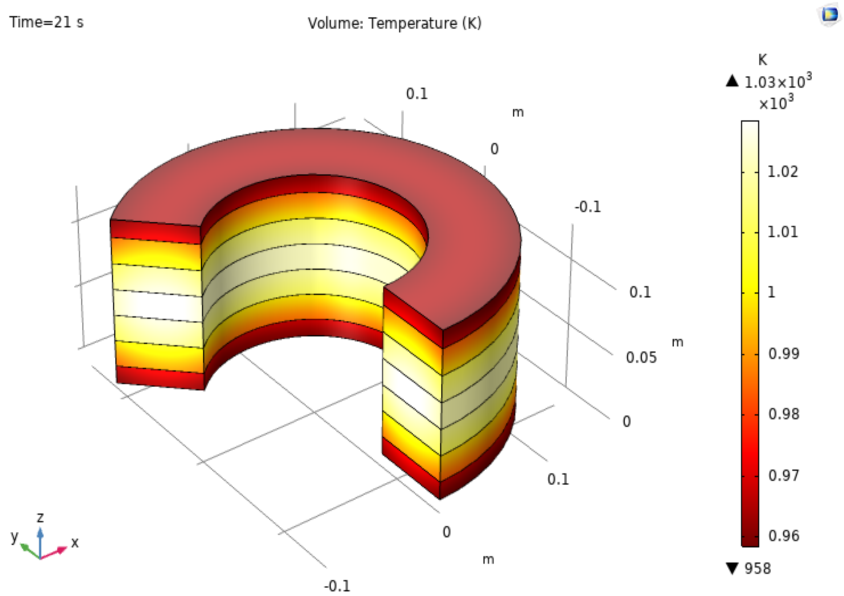

Figure 11. 3D disk brake temperature at t=21sec.

The contact pressure is affected by the heat dissipation during braking due to the material thermal deformation as shown in figure 12 where the contact pressure changes with the disk radius at different selected times. Figure 12 shows that for FS2 different points will get in contact with other points on the contacting friction surfaces or it may have loss of contact. This change in the contact pressure during braking will affect the wear rate and the surface morphology during braking.

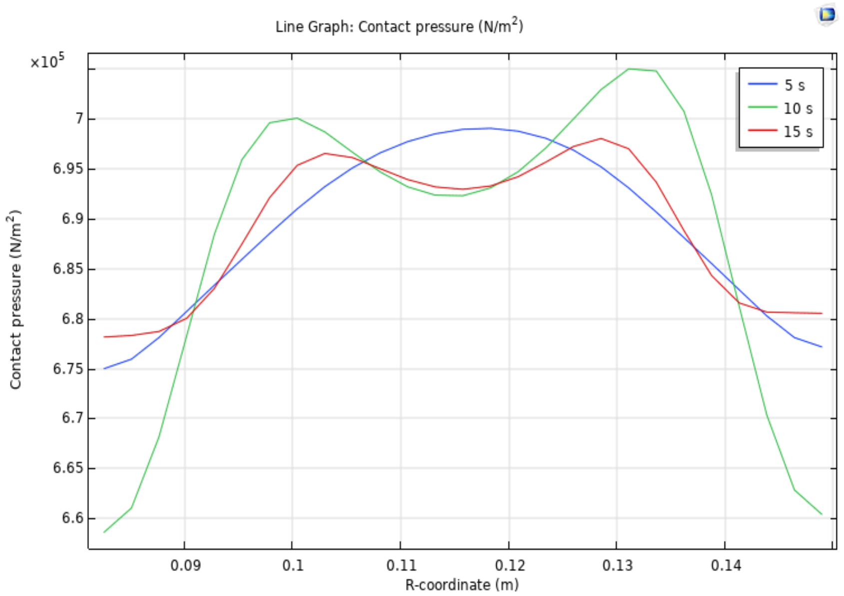

Figure 12. Fs2 contact pressure vs disk radius at various times during braking.

Figure 13 shows the brake disks temperature at t=15sec where the temperature is high at the middle rotor disk at fs3 and fs4, while it has a lower value at the pressure plate and end plate. Figure 13 also shows the 2D disk brake temperature at t=15sec where the temperature increases to about 1000K.

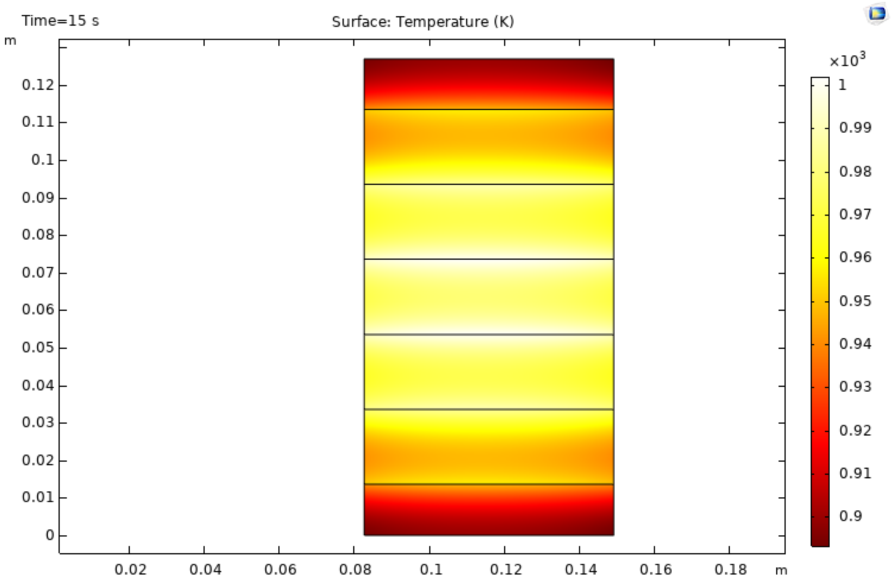

Figure 13. 2D disk brake temperature at t=15sec.

As shown in figure 14, temperature at friction surface number (3) at t=11sec at the middle of the disk is higher than at the ends because the ends of the disks are facing air much more. Also non-uniform contact pressure distribution between disks causes non-uniform temperature at the surfaces that will affect on deformation and so the wear of the contacting surfaces. It is noticed that heat dissipation at the end points of the disks near to the outer radius are cooler than any other points on the disk due to better cooling and better heat dissipation. Disk brakes temperature at the middle of friction surfaces are high and this also will affect the material properties and consequently thermal expansion resulting in some points will loss contact.

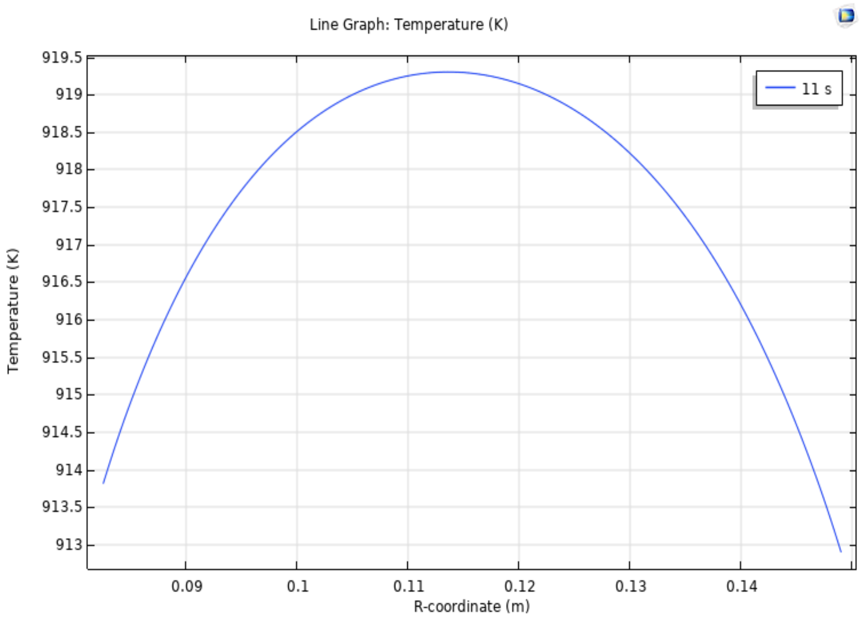

Figure 14. Temperature vs disk radius for fs3 at t=11sec.

Figure 16 shows the inner radius ends temperature numbered from the end plate to the pressure plate from one to eight as shown in figure 15. These results are in agreement with the experimental work and also literature for temperature of c-c composite [1, 4]. The reduction in curve slope is due to the reduction of the aircraft velocity during braking.

Figure 16 shows the points that have the highest temperature on the brake disks where points numbered as 4 and 5 have the highest temperature on the disks.

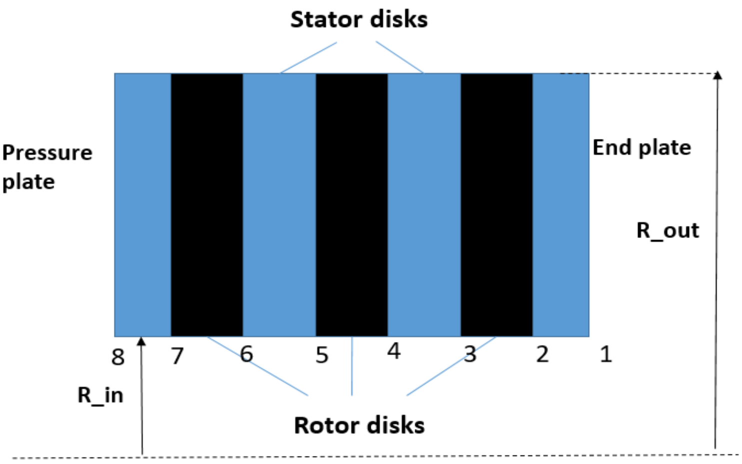

Figure 15. Disk brake numbering points for measuring temperature.

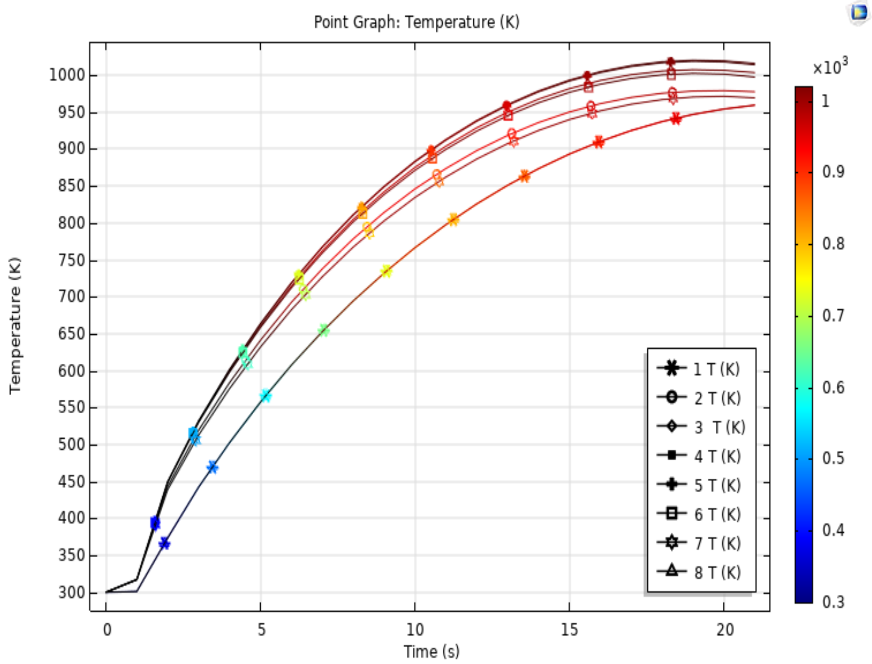

Figure 16. Temperature vs time for different points on the brake disks.

6. Conclusions

The finite element model can be used to simulate the aircraft braking conditions under all conditions. The friction surfaces are the main cause of heat production so it is actually the main heat source for the disks transforming the kinetic energy into heat energy.

The heat generation due to friction will affect the friction material thermal expansion, consequently material thermal deformation. This will affect the contacting points, some points will suffer from loss of contact, and thus all will affect the weight losses and so surface morphology. Heat dissipation at the ends of the disks were better than the middle area of the disk because of better cooling of air forced convection.
The middle rotor disk was found to have the highest temperature of the brake disks. During braking the aircraft velocity is decreasing and this will reduce the heat production due to friction between disks. The model was validated against historical data from literature for Boing 737-400 with cast steel material.

References:

[1] Blanco C, Bermejo J, Marsh H and Menendez R 1997 Chemical and physical properties of carbon as related to brake performance *Wear* **213** 1-12
[2] Orthwein W C 1986 *Clutches and brakes*: Dekker New York)
[3] Di Santo G 2001 Proper Operation of carbon brakes. In: *11th Airbus Performance and Operations Conference, Jalisco, Mexico,*
[4] Chen J and Ju C 1995 Effect of sliding speed on the tribological behavior of a PAN-pitch carbon-carbon composite *Materials chemistry and physics* **39** 174-9
[5] Chen J, Lin J C and Ju C 1996 Effect of load on tribological behaviour of carbon-carbon composites *Journal of materials science* **31** 1221-9
[6] Choi J-H, Han J-H and Lee I 2004 Transient analysis of thermoelastic contact behaviors in composite multidisk brakes *Journal of Thermal Stresses* **27** 1149-67
[7] Zhang C, Zhang L, Zeng Q, Fan S and Cheng L 2011 Simulated three-dimensional transient temperature field during aircraft braking for C/SiC composite brake disc *Materials & Design* **32** 2590-5
[8] Zhao S, Hilmas G E and Dharani L R 2008 Behavior of a composite multidisk clutch subjected to mechanical and frictionally excited thermal load *Wear* **264** 1059-68
[9] Buckley J D and Edie D D 1993 *Carbon-carbon materials and composites* vol 1254: William Andrew)
[10] Bijwe J, Majumdar N and Satapathy B 2005 Influence of modified phenolic resins on the fade and recovery behavior of friction materials *Wear* **259** 1068-78
[11] Belhocine A, Abu Bakar A and Bouchetara M 2014 Numerical Modeling of Disc Brake System in Frictional Contact *Tribology in Industry* **36**
[12] Deng D and Murakawa H 2006 Numerical simulation of temperature field and residual stress in multi-pass welds in stainless steel pipe and comparison with experimental measurements *Computational materials science* **37** 269-77
[13] Kennedy Jr F and Ling F 1974 A thermal, thermoelastic, and wear simulation of a high-energy sliding contact problem
[14] Zhao S, Hilmas G E and Dharani L R 2009 Numerical simulation of wear in a C/C composite multidisk clutch *Carbon* **47** 2219-25
[15] Fitzer E and Manocha L M 2012 *Carbon reinforcements and carbon/carbon composites*: Springer Science & Business Media)
[16] Petinrin M O and Oji J O 2012 Numerical simulation of thermoelastic contact problem of disc brake with frictional heat generation *New York Science Journal* **5** 39-43
[17] Singh H and Shergill H 2012 Thermal Analysis of Disc Brake Using Comsol *International Journal on Emerging Technologies* **3** 84-8
[18] Daidzic N E 2017 Modeling and Computation of the Maximum Braking Energy Speed for Transport Category Airplanes *Journal of Aviation Technology and Engineering* **6** 1