This is the exam of November 4, 2009. All credits for making this exam goes to Mr. Melkert, responsible teacher for this course. All the given graphs are obtained from the reader that goes along with the course.
Part A – Descriptive

Note: all descriptions must be concise, essential, readable and limited in size (maximum 100 words)

A1 – On an airfield in a tropical environment there seems to be a white mist coming from the airco ducting in the cabin. Is this a normal situation and what could be the cause of this?

Answer: This is not an normal situation. It seems that the water evaporator is not working correctly and due to this, air that contains water is blown into the cabin. It can also be the case that the water evaporator cannot handle the humidity of the air in the tropical conditions and hence not all water is removed from the air.

A2 – What would happen if the crew forgets to select the correct cabin-cruise altitude and the aircraft starts flying to cruise altitude?

Answer: If the crew selects the incorrect cabin-cruise setting, then the pressure will be adopted to that level. If the crew even forgets to put in any correct cruise altitude, the pressure in the cabin will be equal to the pressure outside at cruise altitude. This is in general to low for passengers to be able to breath and have enough oxygen.

A3 – Why don't we have the pressure in the cabin during cruise the same as at sea level?

Answer: The pressure difference at cruise will be too high, resulting in a thicker fuselage because it has to withstand higher stresses. This increases the weight again. This weight increase is unwanted.

A4 – Describe what happened with the air that is being used for the environmental control system from the moment it enters the aircraft to the moment it exits the aircraft. Take into account that there are three different airflows you should describe.

Answer: Simple cycle is explained. The air enters the aircraft via the engine where it is compressed, called bleed air. This bleed air has a too high temperature, so it is cooled via heat exchangers, with coolant air. After that the cooled bleed air expands through a turbine. This air is mixed with some cabin and coolant air to reach the right temperature to be blown into the cabin.

Bootstrap cycle: the air is compressed isentropically in the engine or APU compressor, followed by isobaric cooling in the pre-cooler, using external air as coolant. Then there is a secend isentropic compression in a specific compressor and also a second isobaric cooling in a heat exchanger, or inter-cooler, that again uses the external air as a coolant. Finally the air is expanded using a turbine.

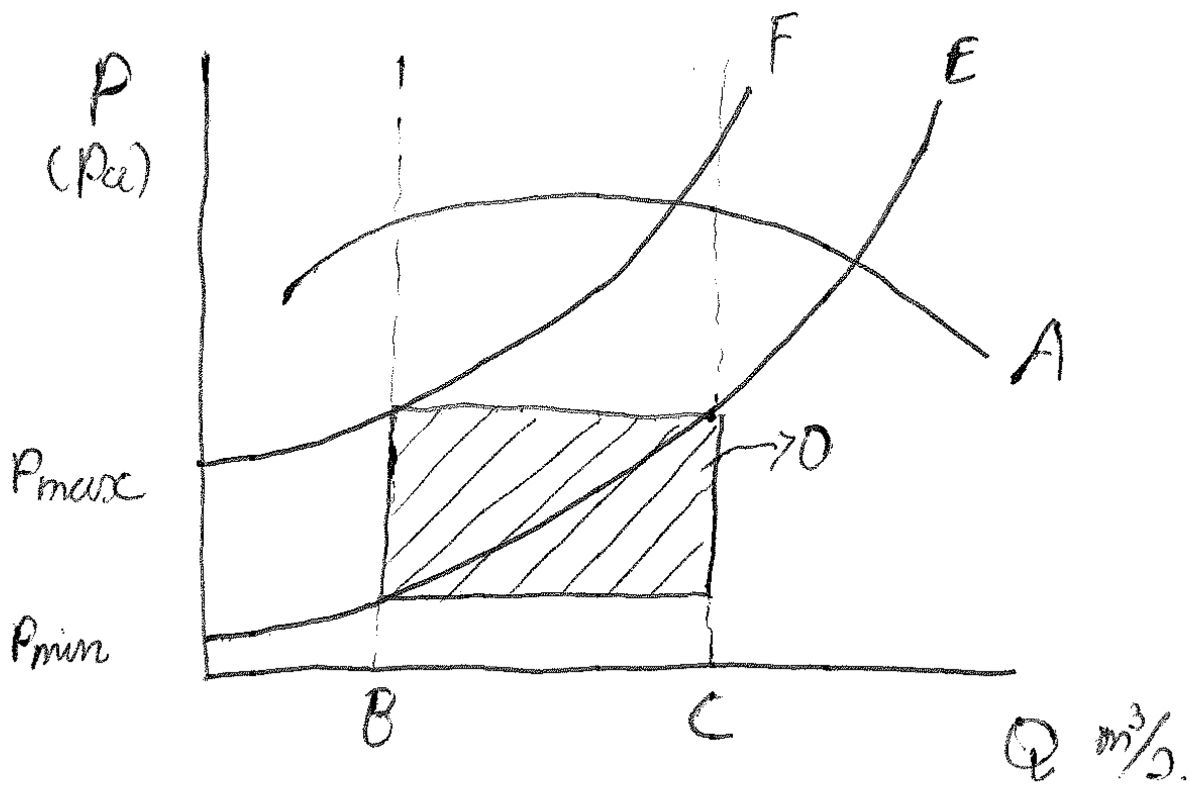
The vapour cycle: first the vapour, typically Freon, is compressed, so the temperature rises. After this, the vapour condensates in an air heat exchanger, with generation of heat and thus heating the air. Now the liquid is laminated through an expansion valve, which reduces the pressure. Now the liquid is evaporated again in an air heat exchanger, where it absorbs heat and cools the air.

A5 – During flight, after approximately 6 hours over the North atlantic, the autopilot in command disengages with a red light and an audible warning signal. The pilot flying takes over, but complains about the fact that his roll steering is impossible, the lateral movement of the steering wheel is rock solid jammed. What could be the cause and what action is may be taken?

Answer: The spoilers might be blocked. During the cruise the speed is too high to have the roll controlled by the ailerons. This will cause to much deflection. The pilot can slow the aircraft down, and then check if the ailerons work. If this is not the case, the pilot can control roll by pumping fuel from one wing tank to the other. The roll movement is used to turn the aircraft, so the pilot can also choose to use thrust vectoring, where the thrust of the left engine is set lower than the right resulting in a change of heading.

A6 – Make a sketch of a diagram in which the fuel pressure and flow rate in a fuel system are represented. Indicate the pump characteristic and the characteristics of the fuel system itself. Indicate all characteristic points by letters (A, B, ….). Additionally describe all these characteristic points in short (maximum one line per point).

Answer: The sketch is as follow:



Line A: Pump characteristic
Line B: Q_{min}; minimum fuel flow requested by the engine
Line C: Q_{max}; maximum fuel flow requested by the engine
Area D: Operational envelope of the engine. Where the bottom part of the rectangle is the minimum pressure that the engine can handle, and the bottom part is the highest pressure the engine can handle.
Line E: The line that represents the minimum pressure to be delivered by the pump to the engine including pressure losses for the minimum pressure.
Line F: The same as the above, but now for maximum pressure.

A7 – Some tires have a maximum allowed rolling speed (e.i. 225 mph). Mention the variables that may become limiting factors for the maximum take-off weight in relation with the given max allowable rolling speed.

Answer: The following holds in order to take-off:

$$L = C_{L_{\max}} \cdot \frac{1}{2} \cdot \rho \cdot V^2 \cdot S = W$$

This means that V can be expressed as:

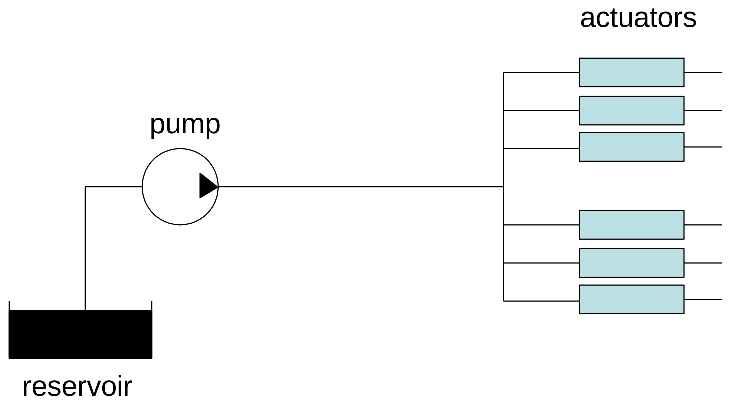
$$V_{take-off} = \sqrt{\frac{W_{MTOW}}{S} \cdot \frac{2}{\rho} \cdot \frac{1}{C_{L_{\max}}}}$$

As can be seen in the above equation, Clmax and W_{MTOW}/S are limiting factors. Because the take-off weight is fixed, this means that you can only change the wing surface S.

Part B – Numerical

Note: If you think you miss a critical parameter for solving the question you may assume a reasonable value for this. Please indicate this clearly. Explain clearly the way in which you reached your answer. Credits will be awarded both for the correct numerical answer and for the approach you have taken to reach this answer. In order to get the maximum score per question you must not only give the final (numerical) answer but also clearly explain how you reached the answer. Derivations of formulae used are not required unless specifically requested or deemed necessary by you but do explain the symbols you used in order to avoid confusion. Answer the questions from an engineering point of view using the knowledge presented in the course and using knowledge gained previously.

B1 – An aircraft is controlled by a hydraulic flight control system. This flight control system operates in total 6 actuators (2 for the rudder, 2 for the elevator and 2 for the ailerons). The simplified lay-out of the hydraulic system consists of a reservoir, a hydraulic pump, the necessary piping and the actuators.



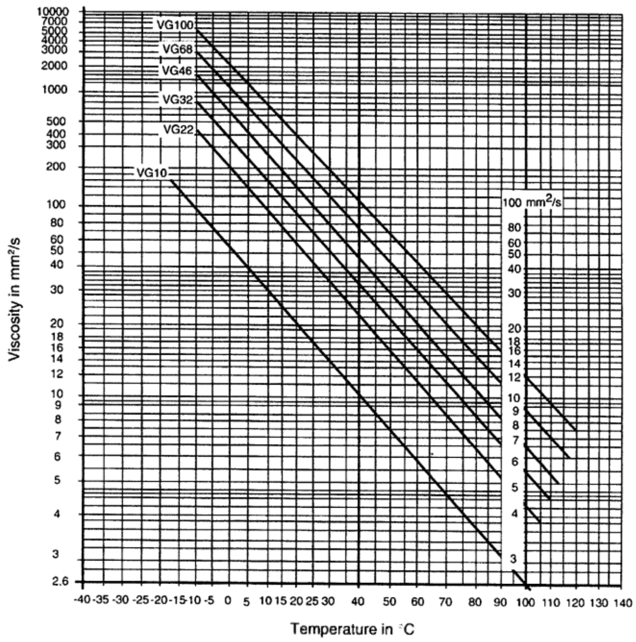
D (pipe inner diameter) = 2.5 inches (1 inch = 25.4 mm)

L (length of piping from the pump to each actuator) = 19 m

ρ (oil density) = 955 kg/m^3

T (temperature of the hydraulic oil) = 30 degrees Centigrade

Type of hydraulic oil: VG32
Q (maximum flow per actuator) = 300 l/min
e/D (relative roughness of the pipe) = 0.0333



a) Calculate the speed of the hydraulic fluid in the hydraulic pipe when 1, 2, 3, 4, 5 or 6 of the actuators are operating simultaneously.

Answer: The speed of the flow can be calculated from the following equation:

$$V_{flow} = \frac{Q_{flow}}{A_{pipe}}$$

The area of the pipe can be determined with:

$$A_{pipe} = \pi \cdot R^2 = \frac{\pi}{4} \cdot (D)^2 = \frac{\pi}{4} \cdot (2.5 \cdot 0.0254)^2 = 3.17 \cdot 10^{-3} \left[m^2 \right]$$

Furthermore it is known that he maximum fuel flow per actuator is 300l/m. From here it is obtained that:

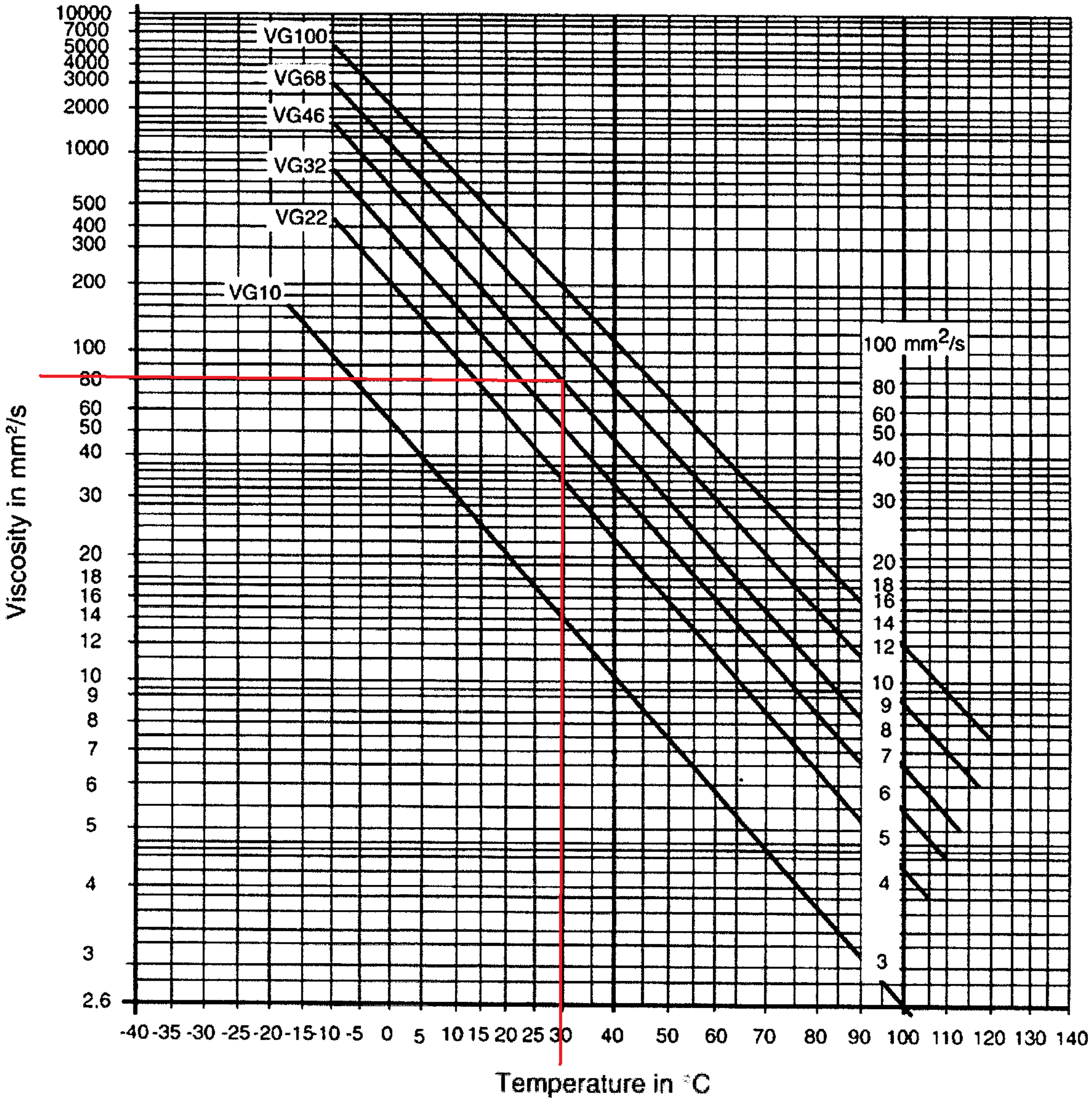
$$Q = 300(l/\min) = \frac{300(l/s)}{60(\min/s)} = 5(l/s) = 0.005(m^3/s)$$

Now everything is known to calculate the velocity, also if more actuators are moving.

Numbers of actuators operating simultaneously	**Q (m^3/s)**	**V (m/s)**
0	**0**	**0**
1	**0.005**	**1.58**
2	**0.010**	**3.16**
3	**0.015**	**4.74**
4	**0.020**	**6.32**
5	**0.025**	**7.89**
6	**0.030**	**9.47**

b) Determine the kinematic viscosity of the hydraulic oil in m^2/s.

Answer: The kinematic viscosity can be simply obtained from the above diagram. For completeness it is repeated underneath.



As can be seen for a temperature of 30˚C the kinematic viscosity is 80 mm²/s, or 80*10⁻⁶ m²/s.

c) Calculate the Reynolds number of the hydraulic fluid in the main pipe when 1, 2, 3, 4, 5 or 6 of the actuators are operating simultaneously.

Answer: The Reynolds number is calculated in the following manner:

$$\mathrm{Re} = \frac{\rho \cdot V_e \cdot D}{\mu}$$

In which V_e is the velocity and μ is the coefficient of viscosity. It is related to the kinematic viscosity as follows:

$$\nu = \frac{\mu}{\rho}$$

This is substituted in the expression for Re to obtain:

$$Re = \frac{\rho \cdot V_e \cdot D}{\nu \cdot \rho} = \frac{V_e \cdot D}{\nu}$$

D and v are both already determined, so the Reynolds number Re can be calculated.

Numbers of actuators operating simultaneously	**Q (m^3/s)**	**V (m/s)**	**Re**
0	**0**	**0**	**0**
1	**0.005**	**1.58**	**1253**
2	**0.010**	**3.16**	**2506**
3	**0.015**	**4.74**	**3760**
4	**0.020**	**6.32**	**5013**
5	**0.025**	**7.89**	**6267**
6	**0.030**	**9.47**	**7519**

d) With the use of Moody's diagram (lecture notes) determine the friction coefficient and determine whether the flow is laminar, turbulent or in between these ranges when 1, 2, 3, 4, 5 or 6 of the actuators are operating simultaneously.

Answer: First the moody diagram is given. This is obtained, as told in the question, via the lecture notes.

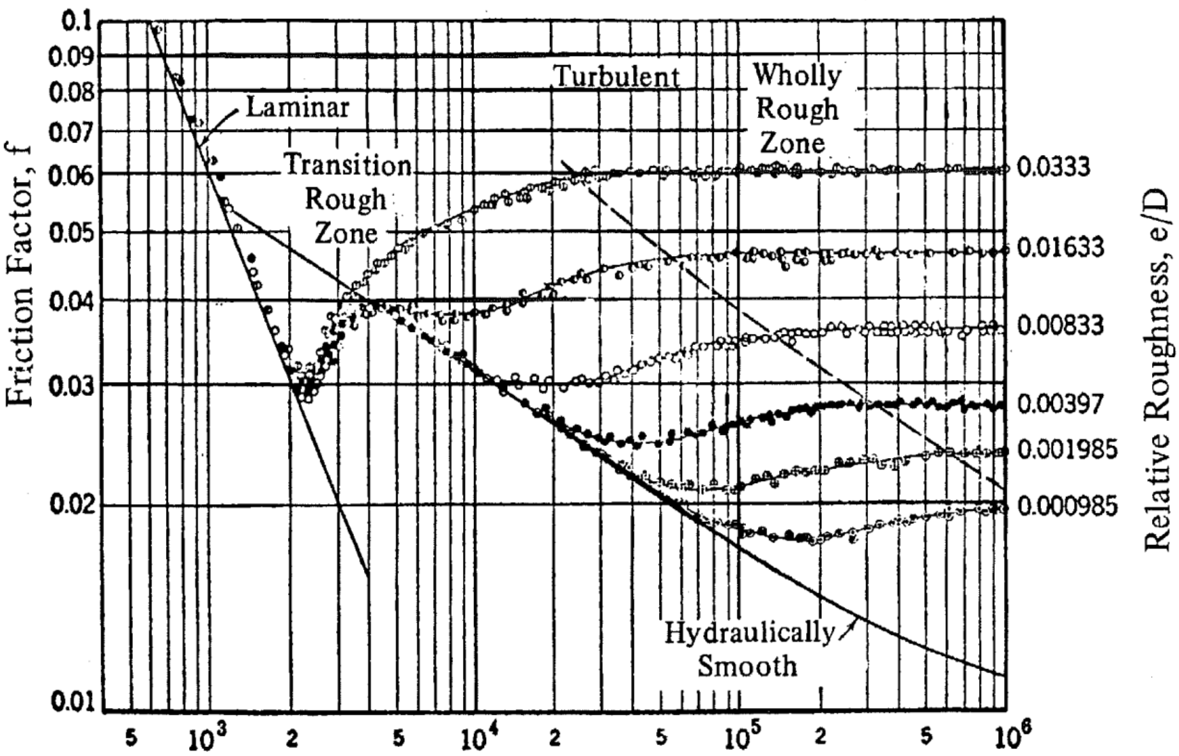


Fig. 2.5 – Moody diagram

The friction coefficient can be obtained from this, it is on the left axis. Note that the relative roughness, e/D, is 0.033. The results are given in the table below.

Numbers of actuators operating simultaneously	**Q (m^3/s)**	**V (m/s)**	**Re**	**f**	**Type of flow**
0	**0**	**0**	**0**	**0**	**-**
1	**0.005**	**1.58**	**1253**	**0.055**	**laminar**
2	**0.010**	**3.16**	**2506**	**0.030**	**transition**
3	**0.015**	**4.74**	**3760**	**0.043**	**transition**
4	**0.020**	**6.32**	**5013**	**0.048**	**transition**
5	**0.025**	**7.89**	**6267**	**0.050**	**transition**

6	**0.030**	**9.47**	**7519**	**0.052**	**transition**

e) Calculate the pressure drop in the pipe (head loss) when 6 actuators are operating simultaneously. You may use the expression for turbulent flow and the relative roughness factor given in the assignment.

Answer: The pressure drop is calculated with the following equation. Note that only the head loss is asked!

$$\Delta p = \left(f \cdot \frac{L}{D} \right) \cdot \frac{1}{2} \cdot \rho \cdot V_e^2$$

From the assignment it is known that f equals 0.06 (turbulent flow, from moody's diagram), L is 19 m, D= 2.5 times 0.0254 m, ρ is 955 kg/m^3 and V_e is 9.47 m/s if all the 6 actuators are moving. Substituting all these values leads to the following result:

$$\Delta p = \left(0.06 \cdot \frac{19}{2.5 \cdot 0.0254} \right) \cdot \frac{1}{2} \cdot 955 \cdot 9.47^2 = 769 \left[kPa \right]$$

B2 – One of the driving tests in developing the undercarriage of a passenger aircraft is the so-called maximum kinetic energy accelerate-stop. In this test the aircraft is speeded up at maximum take-off weight to a certain speed and then stopped using maximum brake performance. This results in maximum heating of the brakes. The requirement requires the brakes to be designed such that there will be no fire for five minutes after this stop. During this five minutes assistance of the fire brigade to cool the brakes is not allowed. Basically this requirement tells the designer to size the brakes for sufficient heat capacity. In this exam question you are required to size the brakes for an airliner.

MTOW = 250,000 kg
Outside air temperature = 32 deg. C
Maximum allowed brake temperature = 585 deg C
Fraction of energy converted to brake heat = 0.82
Decision speed (speed at which the pilot decides to continue or abort the take-off) V_1 = 175 kts
(1 kt = 1.852 km/hr)
Speed at which brakes are applied = V_1 + 20%
Outer diameter brake discs = 0.54 m
Inner diameter brake discs = 0.09 m
Number of braked wheels on the aircraft = 8

Material properties	Carbon	density = 1700 kg/m^3
		specific heat = 1.21 kJ/kg K
	Steel	density = 7800 kg/m^3
		Specific heat = 0.50 kJ/kg K

a) Determine the thickness and mass of the brake assembly per wheel assuming both the stator and rotor brake discs are made from steel.

Answer: First the brake speed is calculated. This is done in the following manner.

$$V_{brake} = V_{decision} \cdot 1.2 = 175 \cdot 1.2 = 210 \left[kts \right]$$

This is converted into m/s in the following way:

$$V_{brake} = \frac{210 kts \cdot 1.852 km/hkts}{3.6 \left(km/h \right) / \left(m/s \right)} = 108.03 \left[m/s \right]$$

Now the simple formula of energy balance is used to calculate the total weight of the brakes. This holds because all kinetic energy of the plane is converted into heat.

The simplified head balance is:

$$k \cdot \frac{1}{2} \cdot M \cdot v^2 = m_{total,brakes} \cdot c_v \cdot \Delta T$$

This is rewritten to:

$$m_{total,brakes} = \frac{k \cdot \frac{1}{2} \cdot M \cdot v^2}{c_v \cdot \Delta T}$$

Now M is the mass of the airplane, 250,000 kg, k is the fraction of energy converted to brake heat, v is the brake velocity, c_v is the heat specific heat and ΔT is the temperature increment during braking.
If all these values are substituted, it is obtained that:

$$m_{total,brakes} = \frac{0.81 \cdot \frac{1}{2} \cdot 250,000 \cdot 108,03^2}{0.50 \cdot 10^3 \cdot (585-32)} = 4273.81[kg]$$

The weight per wheel is simply obtained by dividing by the number of wheels, in this case 8. Now that the mass per wheel is known, and also the density is known, the required volume per wheel can be obtained.

$$V_{brake} = \frac{m_{brake}}{\rho_{brake}} = \frac{534.23(kg)}{7800(kg/m^3)} = 0.0685\left[m^3\right]$$

The area of the disk can also be calculated. This is shown in the following equation.

$$A_{brake} = \pi \cdot R^2 = \frac{\pi}{4} \cdot \left(D_{outer} - D_{inner}\right)^2 = \frac{\pi}{4} \cdot (0.54-0.09)^2 = 0.159\left[m^2\right]$$

Now the thickness can be obtained by dividing the volume of the brake by the area of the brake.

$$t_{brake} = \frac{V_{brake}}{A_{brake}} = \frac{0.0685}{0.159} = 0.43[m]$$

b) Determine the effect on brake mass when the decision speed is lowered by 10 kts

Asnwer: The velocity is decreased by 10 kts, meaning v=165 kts. Now the speed at which the brakes are applied is:

$$V_{brake} = V_{decision} \cdot 1.2 = 165 \cdot 1.2 = 198[kts]$$

This is:

$$V_{brake} = \frac{198kts \cdot 1.852km/hkts}{3.6(km/h)/(m/s)} = 101.86[m/s]$$

This is substituted in the following equation to obtain the new total weight.

$$m_{total,brakes} = \frac{0.81 \cdot \frac{1}{2} \cdot 250,000 \cdot 101,86^2}{0.50 \cdot 10^3 \cdot (585-32)} = 3799.33[kg]$$

This is a reduction in total weight of 474.48 kg.

c) What could you do to lower the decision speed by 10 kts? Give at least three possible solutions.

Answer: The following suggestions are done:

- **Increase Cl max for take-off**
- **Lower wing loading (W/S)**

These improvement because the decision speed is closely related to the speed at which the aircraft takes off. If the aircraft takes of the produced lift most equal the weight of the aircraft.

$$L = C_{L_{\max}} \cdot \frac{1}{2} \cdot \rho \cdot V^2 \cdot S = W$$

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d) Now assume that the rotor discs are made from carbon and the stator discs are made from steel. Furthermore assume that the number of stator discs is one more than the number of rotor discs. The thickness of both stator and rotor discs is 20 mm each. Determine the number of rotor and stator discs per wheel. Assume V_1 to be 175 kts again.

Answer: The number of rotor discs is assumed to be n. The number of stator discs is then n+1. The thickness of the discs is already defined to be 0.02 m. This allows the volume of the disc to be calculated.

$$V_{brake} = \pi \cdot R^2 = \frac{\pi}{4} \cdot \left(D_{outer} - D_{inner}\right)^2 \cdot t = \frac{\pi}{4} \cdot \left(0.54 - 0.09\right)^2 \cdot 0.02 = 3.18 \cdot 10^{-3} \left[m^3\right]$$

From this the mass of a rotor disc, made out of carbon, and the mass of a stator disc, made out of steel, can be calculated.

$$m_{rotor} = V_{disc} \cdot \rho = 3.18 \cdot 10^{-3} \cdot 1700 = 5.41 \left[kg\right]$$

$$m_{stator} = V_{disc} \cdot \rho = 3.18 \cdot 10^{-3} \cdot 7800 = 24.81 \left[kg\right]$$

Now this is substituted into the simple formula of energy balance. Note that there are in total 8 wheels, hence the factor 8.

$$k \cdot \frac{1}{2} \cdot M \cdot v^2 = 8 \cdot \left(m_{roter} \cdot c_{v,carbon} \cdot n + m_{stator} \cdot c_{v,steel} \cdot \left(n+1\right)\right) \cdot \Delta T$$

All the values in the above equation are known, hence the equation can be solved for n.

$$n = \frac{\dfrac{k \cdot \frac{1}{2} \cdot M \cdot v^2}{8 \cdot \Delta T} - m_{stator} \cdot c_{v,steel}}{m_{roter} \cdot c_{v,carbon} + m_{stator} \cdot c_{v,steel}}$$

It turns out that n is 13.61. Of course there are not 0.61 discs, so this must be rounded off to the next highest integer. So n equals 14.

e) What is the weight saving for the complete aircraft you achieve by doing so?

Answer: The weight is obtained by performing the following calculation.

$$m_{tot} = \left(n+1\right) \cdot m_{stator} + n \cdot m_{rotor} = \left(14+1\right) \cdot 24.81 + 14 \cdot 5.41 = 447.87 \left[kg\right]$$

For all the 8 wheels the weight will be 3582.92 kg, resulting in a weight reduction of 216.41 kg. Note that also the thickness is larger, now it is 0.58 m (29*0.02).