**ISABE 2022 Workshop**

**Tutorial Worksheet**

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| Design point performance – 1-spool turbojet engine **(Classroom Example)** |



Compressor exit temperature, T3 = \_\_\_\_\_\_\_\_\_\_\_\_\_ K

Compressor work, CW = \_\_\_\_\_\_\_\_\_\_\_ MW

Combustor heat input, Qin = \_\_\_\_\_\_\_\_ MW

Fuel flow, Wff = \_\_\_\_\_\_\_\_\_ kg/s

Turbine exit temperature, T7 = \_\_\_\_\_\_\_\_\_\_\_ K

Turbine exit pressure, P7 = \_\_\_\_\_\_\_\_\_\_ bar

Nozzle exit pressure, P8 = \_\_\_\_\_\_\_\_\_ bar

Nozzle exit temperature (static), t8 = \_\_\_\_\_\_\_\_\_\_ K

Nozzle exit velocity, V8 = \_\_\_\_\_\_\_\_\_ m/s

Nozzle exit area, A = \_\_\_\_\_\_\_\_\_ m2

Thrust, FN = \_\_\_\_\_\_\_\_\_\_ N

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| Off-design performance – 1-spool turbojet (PCN =0.7) |

**Iteration 1**

Guessed pressure ratio = \_\_\_\_\_\_\_\_\_\_\_\_

From compressor map, corresponding NDMF = \_\_\_\_\_\_\_\_\_\_\_\_\_

From compressor map, corresponding efficiency = \_\_\_\_\_\_\_\_\_\_\_

Compressor exit temperature, T3 = \_\_\_\_\_\_\_\_ K

Guessed ΔT45 from combustor map = \_\_\_\_\_\_\_\_\_ K

Combustor exit temperature, T5 = \_\_\_\_\_\_\_\_\_\_\_ K

Combustor heat input, Qin = \_\_\_\_\_\_\_\_\_\_\_ MW

Combustor fuel flow, Wff = \_\_\_\_\_\_\_\_\_\_\_ kg/s

Guessed turbine ΔH/T = \_\_\_\_\_\_\_\_\_\_\_

Corresponding turbine NDMF \* CN = \_\_\_\_\_\_\_\_\_\_

Corresponding turbine efficiency = \_\_\_\_\_\_\_\_\_\_

Turbine exit temperature, T7 = \_\_\_\_\_\_\_\_\_\_\_ K

Turbine exit pressure, P7 = \_\_\_\_\_\_\_\_\_\_\_ bar

Rotational compatibility = Yes/No

Mass flow compatibility = Yes/No

Work compatibility = Yes/No

**Iteration 1**

Guessed pressure ratio = \_\_\_\_\_\_\_\_\_\_\_\_

From compressor map, corresponding NDMF = \_\_\_\_\_\_\_\_\_\_\_\_\_

From compressor map, corresponding efficiency = \_\_\_\_\_\_\_\_\_\_\_

Compressor exit temperature, T3 = \_\_\_\_\_\_\_\_ K

Guessed ΔT45 from combustor map = \_\_\_\_\_\_\_\_\_ K

Combustor exit temperature, T5 = \_\_\_\_\_\_\_\_\_\_\_ K

Combustor heat input, Qin = \_\_\_\_\_\_\_\_\_\_\_ MW

Combustor fuel flow, Wff = \_\_\_\_\_\_\_\_\_\_\_ kg/s

Guessed turbine ΔH/T = \_\_\_\_\_\_\_\_\_\_\_

Corresponding turbine NDMF \* CN = \_\_\_\_\_\_\_\_\_\_

Corresponding turbine efficiency = \_\_\_\_\_\_\_\_\_\_

Rotational compatibility = Yes/No

Mass flow compatibility = Yes/No

Work compatibility = Yes/No

**Performance calculation**

Nozzle exit pressure, P8 = \_\_\_\_\_\_\_\_\_ bar

Nozzle exit temperature (static), t8 = \_\_\_\_\_\_\_\_\_\_ K

Nozzle exit velocity, V8 = \_\_\_\_\_\_\_\_\_ m/s

Thrust, FN = \_\_\_\_\_\_\_\_\_\_ N

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| **Simulation Exercise 1**  |

|  |  |  |
| --- | --- | --- |
| SL | Operating condition | Compressor |
| Pressure ratio | Exit temperature | Efficiency | Work |
| 1 | Design point |  |  |  |  |
| TET = 1141K |
| 2 | OP1 |  |  |  |  |
| TET = 900K |
| 3 | OP2 |  |  |  |  |
| TET = 1000K |
| 4 | OP3 |  |  |  |  |
| TET = 1200K |
| 5 | OP4 |  |  |  |  |
| TET = 1300K |

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| --- | --- | --- |
| SL | Operating condition | Turbine |
| Pressure ratio | Exit temperature | Efficiency | Work |
| 1 | Design point |   |   |   |   |
| TET = 1141K |
| 2 | OP1 |   |   |   |   |
| TET = 900K |
| 3 | OP2 |   |   |   |   |
| TET = 1000K |
| 4 | OP3 |   |   |   |   |
| TET = 1200K |
| 5 | OP4 |   |   |   |   |
| TET = 1300K |

|  |  |  |
| --- | --- | --- |
| SL | Operating condition | Performance |
| Net thrust | SFC | Mass flow | Fuel flow |
| 1 | Design point |   |   |   |   |
| TET = 1141K |
| 2 | OP1 |   |   |   |   |
| TET = 900K |
| 3 | OP2 |   |   |   |   |
| TET = 1000K |
| 4 | OP3 |   |   |   |   |
| TET = 1200K |
| 5 | OP4 |   |   |   |   |
| TET = 1300K |

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| **Simulation Exercise 2** |

|  |  |  |
| --- | --- | --- |
| SL | Operating condition | Compressor |
| Pressure ratio | Exit temperature | Efficiency | Work |
| 1 | Design point |  |  |  |  |
| 0, 0, 0 |
| 2 | OP1 |  |  |  |  |
| 0, -15, 0 |
| 3 | OP2 |  |  |  |  |
| 2000, -10, 0.5 |
| 4 | OP3 |  |  |  |  |
| 5000, 0, 0.6 |
| 5 | OP4 |  |  |  |  |
| 8000, 10, 0.7 |
| 6 | OP5 |  |  |  |  |
| 10000, 0, 0.8 |
| 7 | OP6 |  |  |  |  |
| 6000, 20, 0.8 |
| 8 | OP7 |  |  |  |  |
| 0, 0, 0.6 |

|  |  |  |
| --- | --- | --- |
| SL | Operating condition | Turbine |
| Pressure ratio | Exit temperature | Efficiency | Work |
| 1 | Design point |  |  |  |  |
| 0, 0, 0 |
| 2 | OP1 |  |  |  |  |
| 0, -15, 0 |
| 3 | OP2 |  |  |  |  |
| 2000, -10, 0.5 |
| 4 | OP3 |  |  |  |  |
| 5000, 0, 0.6 |
| 5 | OP4 |  |  |  |  |
| 8000, 10, 0.7 |
| 6 | OP5 |  |  |  |  |
| 10000, 0, 0.8 |
| 7 | OP6 |  |  |  |  |
| 6000, 20, 0.8 |
| 8 | OP7 |  |  |  |  |
| 0, 0, 0.6 |

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| --- | --- | --- |
| SL | Operating condition | Performance |
| Net thrust | SFC | Mass flow | Fuel flow |
| 1 | Design point |  |  |  |  |
| 0, 0, 0 |
| 2 | OP1 |  |  |  |  |
| 0, -15, 0 |
| 3 | OP2 |  |  |  |  |
| 2000, -10, 0.5 |
| 4 | OP3 |  |  |  |  |
| 5000, 0, 0.6 |
| 5 | OP4 |  |  |  |  |
| 8000, 10, 0.7 |
| 6 | OP5 |  |  |  |  |
| 10000, 0, 0.8 |
| 7 | OP6 |  |  |  |  |
| 6000, 20, 0.8 |
| 8 | OP7 |  |  |  |  |
| 0, 0, 0.6 |

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| **Simulation Exercise 3** |

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| --- | --- | --- |
| Operating condition | Compressor faults | Turbine faults |
| PR Deg | FC Deg | ETA Deg | DH deg | TF deg | ETA deg |
| OP1 | 0% | -1% | -2% | 0% | 0% | 0% |
| OP2 | -2% | 0% | 0% | 0% | 0% | -2% |
| OP3 | 0% | 0% | 0% | -1% | 0% | -3% |
| OP4 | -1% | -1% | -3% | 0% | 0% | 0% |
| OP5 | 0% | 0% | -4% | 0% | 0% | -2% |
| OP6 | 0% | 0% | 0% | -2% | -3% | 0% |
| OP7 | -3% | 2% | -3% | 0% | -1% | -1% |
| OP8 | 0% | 1% | 0% | 0% | -2% | -3% |

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| --- | --- | --- |
| SL | Operating condition | Compressor |
| Pressure ratio | Exit temperature | Efficiency | Work |
| 1 | Design point |   |   |   |   |
|  |
| 2 | OP1  |   |   |   |   |  |
|  |
| 3 | OP2 |   |   |   |   |  |
|  |
| 4 | OP3 |   |   |   |   |  |
|  |
| 5 | OP4 |   |   |   |   |  |
|  |
| 6 | OP5 |   |   |   |   |  |
|  |
| 7 | OP6 |   |   |   |   |  |
|  |
| 8 | OP7 |   |   |   |   |  |
|  |
| 9 | OP8 |   |   |   |   |  |
|  |

|  |  |  |
| --- | --- | --- |
| SL | Operating condition | Turbine |
| Pressure ratio | Exit temperature | Efficiency | Work |
| 1 | Design point |   |   |   |   |
|  |
| 2 | OP1  |   |   |   |   |  |
|  |
| 3 | OP2 |   |   |   |   |  |
|  |
| 4 | OP3 |   |   |   |   |  |
|  |
| 5 | OP4 |   |   |   |   |  |
|  |
| 6 | OP5 |   |   |   |   |  |
|  |
| 7 | OP6 |   |   |   |   |  |
|  |
| 8 | OP7 |   |   |   |   |  |
|  |
| 9 | OP8 |   |   |   |   |  |
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| --- | --- | --- |
| SL | Operating condition | Power Turbine |
| Pressure ratio | Exit temperature | Efficiency | Work |
| 1 | Design point |   |   |   |   |
|  |
| 2 | OP1  |   |   |   |   |  |
|  |
| 3 | OP2 |   |   |   |   |  |
|  |
| 4 | OP3 |   |   |   |   |  |
|  |
| 5 | OP4 |   |   |   |   |  |
|  |
| 6 | OP5 |   |   |   |   |  |
|  |
| 7 | OP6 |   |   |   |   |  |
|  |
| 8 | OP7 |   |   |   |   |  |
|  |
| 9 | OP8 |   |   |   |   |  |
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| --- | --- | --- |
| SL | Operating condition | Performance |
| Shaft Power | SFC | Mass flow | Fuel flow |
| 1 | Design point |   |   |   |   |
|  |
| 2 | OP1  |   |   |   |   |  |
|  |
| 3 | OP2 |   |   |   |   |  |
|  |
| 4 | OP3 |   |   |   |   |  |
|  |
| 5 | OP4 |   |   |   |   |  |
|  |
| 6 | OP5 |   |   |   |   |  |
|  |
| 7 | OP6 |   |   |   |   |  |
|  |
| 8 | OP7 |   |   |   |   |  |
|  |
| 9 | OP8 |   |   |   |   |  |
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| **Simulation Exercise 4**  |



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| --- | --- | --- |
| Operating condition | Time (mins) | Input |
| Altitude (m) | Mach number | PCN |
| Taxi | 5 | 0 | 0 | 0.7 |
| Takeoff | 1 | 0 | 0 | 1.1 |
| Climb 1 | 5 | 3000 | 0.5 | 0.9 |
| Climb 2 | 10 | 7000 | 0.7 | 0.8 |
| Cruise | 123 | 10000 | 0.8 | 1 |
| Low Rating | 30 | 5000 | 0.75 | 0.7 |
| Reverse Thrust | 1 | 0 | 0.4 | 1.1 |
| Taxi | 5 | 0 | 0 | 0.7 |



Assuming that we have been able to determine the operating temperatures and
stress levels, from the Larson-Miller chart we can provide the parameter P in
the equation:

$$P= \frac{T}{1000}(Log t\_{f}+20)$$

Where,
T = Temperature K (TET)
tf = Time to failure

The TET-Stress correlation is provided below:

|  |  |
| --- | --- |
| **TET (K)** | **Stress (MPa)** |
| **1570** | 350 |
| **1525** | 300 |
| **1290** | 265 |
| **1215** | 250 |
| **1070** | 200 |
| **1040** | 150 |
| **900** | 100 |

The stress-LMP correlation is provided below:

|  |  |
| --- | --- |
| **Stress (MPa)** | **P** |
| **100** | 37.0 |
| **150** | 36.0 |
| **200** | 35.0 |
| **250** | 34.5 |
| **265** | 34.1 |
| **300** | 34.0 |
| **350** | 33.9 |

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Operating condition | Time (mins) | Input | Output | Stress (Mpa) | P | tf (hours) |
| Altitude (m) | Mach number | PCN | Net Thrust | Fuel flow | Turbine inlet T11  |
| Taxi | 5 | 0 | 0 | 0.7 |  |  |  |  |  |  |
| Takeoff | 1 | 0 | 0 | 1.1 |  |  |  |  |  |  |
| Climb 1 | 5 | 3000 | 0.5 | 0.9 |  |  |  |  |  |  |
| Climb 2 | 10 | 7000 | 0.7 | 0.8 |  |  |  |  |  |  |
| Cruise | 123 | 10000 | 0.8 | 1 |  |  |  |  |  |  |
| Low Rating | 30 | 5000 | 0.75 | 0.7 |  |  |  |  |  |  |
| Reverse Thrust | 1 | 0 | 0.4 | 1.1 |  |  |  |  |  |  |
| Taxi | 5 | 0 | 0 | 0.7 |  |  |  |  |  |  |

|  |  |  |  |
| --- | --- | --- | --- |
| Operating condition | Time (mins) | tf (hours) | T/tf |
|
| Taxi | 5 |  |  |
| Takeoff | 1 |  |  |
| Climb 1 | 5 |  |  |
| Climb 2 | 10 |  |  |
| Cruise | 123 |  |  |
| Low Rating | 30 |  |  |
| Reverse Thrust | 1 |  |  |
| Taxi | 5 |  |  |
| Total | 180 |  |  |

* Total number of cycles using Miner’s Law, N = 1/(Total T/tf)

= \_\_\_\_\_\_\_\_\_\_\_\_

* Applying FOS = 1.5, the number of cycles, Nfos = N/1.5

= \_\_\_\_\_\_\_\_\_\_\_\_

* Total number of hours before failure criteria, T = Nfos x 180/60

= \_\_\_\_\_\_\_\_\_\_\_\_\_

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| **Simulation exercise 5** |

Using -3 in compressor efficiency degradation index (%) to represent fan degradation

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Operating condition | Time (mins) | Input | Output | Stress (Mpa) | P | tf (hours) |
| Altitude (m) | Mach number | PCN | Thrust | Fuel flow | Turbine inlet T11 |
| Taxi | 5 | 0 | 0 | 0.7 |  |  |  |  |  |  |
| Takeoff | 1 | 0 | 0 | 1.1 |  |  |  |  |  |  |
| Climb 1 | 5 | 3000 | 0.5 | 0.9 |  |  |  |  |  |  |
| Climb 2 | 10 | 7000 | 0.7 | 0.8 |  |  |  |  |  |  |
| Cruise | 123 | 10000 | 0.8 | 1 |  |  |  |  |  |  |
| Low Rating | 30 | 5000 | 0.75 | 0.7 |  |  |  |  |  |  |
| Reverse Thrust | 1 | 0 | 0.4 | 1.1 |  |  |  |  |  |  |
| Taxi | 5 | 0 | 0 | 0.7 |  |  |  |  |  |  |

|  |  |  |  |
| --- | --- | --- | --- |
| Operating condition | Time (mins) | tf (hours) | T/tf |
|
| Taxi | 5 |  |  |
| Takeoff | 1 |  |  |
| Climb 1 | 5 |  |  |
| Climb 2 | 10 |  |  |
| Cruise | 123 |  |  |
| Low Rating | 30 |  |  |
| Reverse Thrust | 1 |  |  |
| Taxi | 5 |  |  |
| Total | 180 |  |  |

* Total number of cycles using Miner’s Law, N = 1/(Total T/tf)

= \_\_\_\_\_\_\_\_\_\_\_\_

* Applying FOS = 1.5, the number of cycles, Nfos = N/1.5

= \_\_\_\_\_\_\_\_\_\_\_\_

* Total number of hours before failure criteria, T = Nfos x 180/60

= \_\_\_\_\_\_\_\_\_\_\_\_\_