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Conceptual Design of Aeroderivative Industrial Gas Turbines

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Designing and manufacturing turbine engines have many complexities and challenges that need time and cost. Therefore, reputable companies producing gas turbines have always sought to shorten the design and construction processes, one of which is to use the core of aerial gas turbines in industrial gas turbines. This category of industrial gas turbines is called aero-derivative gas turbines. Aerial gas turbines can be used as industrial gas turbines due to their particular characteristics such as lightweight, relatively small dimensional size, high efficiency, and performance. These characteristics can shorten the design and manufacturing process. In the present work, ALF 502 aero gas turbine has been studied to convert its application to the derived industrial gas turbine. GasTurb software has been used to model this gas turbine for industrial applications. In this study, six different scenarios have been studied for converting aero engines to industrial engines, and results have been discussed. Finally, three scenarios were selected to be implemented on this engine among the studied scenarios.

Keywords: *Industrial Gas turbine, Derived Gas Turbine, Modified Engine, Turbine Engines, Gas Generator*

Introduction

All gas turbines except aerial gas turbines are known as industrial gas turbines. Industrial gas turbines are turboshaft engines used in various industries such as oil, gas, petrochemicals as generator actuators, compressors, pumps, and thermal power plants as generator actuators.

Initially, gas turbines were mainly used in the aviation industry. The use of gas turbines in industry expanded with the increase in demand for electrical energy and the need to use low-volume machines, low initial capital, and short start-up time to convert thermal energy into mechanical work. Unlike aerial gas turbines, industrial gas turbines have no limitations in size and weight, and their velocity of the exhaust gas is almost zero. In addition, the operating time of these engines is very long, about 100,000 working hours.

Industrial gas turbines are divided into different groups by different individuals and companies. These divisions are generally done by taste and, in many cases, differ from each other. In one of the most popular divisions, industrial gas turbines with simple cycles are divided into five groups mentioned below [1].

Heavy-duty gas turbines:

These gas turbines are large power generation units with a power generation range between 3 to 480 MW with a simple cycle. The efficiency of this turbine is between 30 to 46%.

Gas turbines derived from aero engines: As their name suggests, these power generation units are aero engines that have been used to generate electrical power by modifying their structure. These turbines have a power range of 3 to about 50 MW, and their thermal efficiency is between 35 and 45%.

Industrial Gas Turbines:

These turbines have a power generation range between 2.5 to 15 MW. These turbines are initially designed for industrial use, and their efficiency is less than 30%.

Mini Gas Turbines:

These gas turbines have a power range of 0.5 to 2.5 MW. Due to the low volume, they generally use a compressor and centrifugal turbine. Their efficiency is between 15 to 25%.

Micro Gas Turbines:

These turbines produce power between 20 and 350 kW. These turbines have expanded in the last two decades.

Aeroderivative gas turbines

Today, the use of derived industrial gas turbines technology has improved the thermodynamic performance of industrial gas turbines and provided the conditions for using these engines where there is a simultaneous demand for thermal and mechanical energy. Compared to heavy gas turbines, these turbines have higher efficiency and more flexibility in the medium power range and offer better thermal efficiency, start-up time, maintenance, and weight. Also, derived industrial gas turbines have a higher compression ratio than heavy gas turbines due to their multi-spool feature. Furthermore, their performance is improved if internal cooling technologies are used. The weight of these gas turbines, which is very light, is significant in some applications, such as offshore applications and industries. Also, their lightweight reduces heat loads, resulting in better thermal transfer and faster cooling and heating of the engine when the engine is turned on and off. More importantly, this can be a competitive factor in applications where transportation and installation costs are more critical, such as the oil and gas industry [1].

Rolls-Royce, a British company, and General Electric, an American company, have contributed a lot to aero-derivative gas turbines. MT30, Trent 60, LM6000, LM2500, and LM1600 gas turbines are successful examples. There is limited information about this technology as it is recently developed. What is certain is that the two companies, which largely control the gas turbine technologies, have refused to provide any information on the conversion of an aero-engine to an industrial gas turbine. However, by examining the existing samples and the structural differences of these gas turbines with their central cores, which are mostly turbofan engines, it is evident that the following changes are required to convert an aero-engine into an industrial gas turbine:

- Reinforcing the bearing
- Replacing the fan with several stages of compressor
- Replacing the combustion chamber system so that it can burn with less expensive fuels
- Adding a power turbine
- Reducing the ratio of the designed gearbox so that it fits the type of load in particular (for example, power generator, ship propeller, gas or liquid pumps)
- Adjusting the engine to extend its life
- Adding a heat exchanger if possible
- Increasing the duct length between the gas generator and the free power turbine to handle differences in diameters in some power generation applications where a free power turbine is connected directly to a gas generator with a larger diameter.

Selecting the aero engine to change its application

To select an aero-engine model to change its application to industrial mode, it is necessary to consider things such as the availability of the engine, the required infrastructure, the possible changes needed for the gas generating core, the amount of power required, the geometrical dimensions of the engine, the amount of access to engine design information, number of possible changes required (less is better), and the history of using this engine for producing derived engines in

other countries. Based on the above factors, ALF 502 turbofan was selected, which is used in BAE 146 aircraft, four engines are used in this aircraft. After performing field research, it was found that a sufficient number of these engines are available in Iran. Some of these engines are not used in aircraft anymore. However, it is possible to change their application to industrial mode, which is advantageous. Also, some repair and maintenance centers of this engine are available in Iran with good experience. Also, since the core of this engine was initially a turboshaft engine that has been converted to turbofan mode after the changes, it can be a suitable engine to change its application to an industrial engine.

ALF502 engine specifications

This aero engine is a twin-spool turbofan engine with a 5.7:1 bypass ratio that has been designed by the changes in the Lycoming T55 turboshaft engine. The engine consists of a fan stage, one stage of the low-pressure compressor, seven stages of axial high-pressure compressor, one stage of radial high-pressure compressor, an annular combustion chamber, two stages of high-pressure turbine, and two stages of the low-pressure turbine, which is capable of 31 KN thrust. Figure 1 shows this engine.
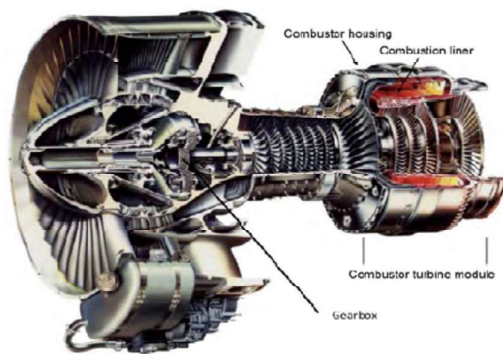

Figure 1: ALF502 engine

This engine's geometric and functional specifications can be seen in table 1. These specifications will be used as input data to the GasTurb software and validate the results obtained from the software.

Table 1: Geometric and functional specifications of ALF502 engine at the design point

Height	M	0
Standard temperature	K	288.17
Standard pressure	kPa	101.353
High-pressure compressor pressure ratio	-	7.84
Inlet temperature of the first turbine	K	1403.89
Total mass flow rate	kg/sec	112.945
Bypass ratio	-	5.7
Fan speed	rpm	5245
High-pressure spool speed	rpm	19180
Total net thrust	kN	31.137
Special fuel consumption	kg/hr.kN	41.4
Polytropic fan efficiency	-	0.88
Polytropic efficiency of the low-pressure compressor	-	0.86
Polytropic efficiency of the high-pressure compressor	-	0.858
Combustion chamber efficiency	-	0.98
Polytropic efficiency of the high-pressure turbine	-	0.897
Low-pressure turbine efficiency	-	0.871
Mechanical efficiency of the high-pressure spool	-	0.993
Mechanical efficiency of the low-pressure spool	-	0.985

GasTurb Software Presentation

GasTurb is modeling software for aero engines and industrial turbines developed by Kurzke. This software is written using Fortran language and allows the user to perform thermodynamic cycle calculations at the design and off-design point. This software can model gas turbine engines with different single spool, twin-spool, and triple spool configurations. Also, it can define different components such as coolers, recuperators, heaters, and others. One of the advantages of this software is that it runs graphically, which makes it user-friendly. Figure 2 shows the first page of this software. As seen in the image, in the upper bar of the main window, the engine type, and the desired configuration are selected, and at the bottom of the

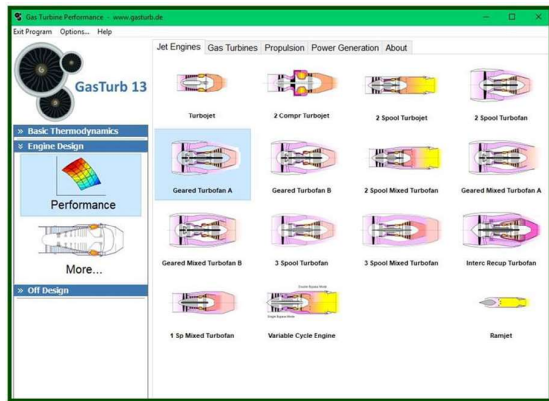page, the calculation type (design or off-design point) is selected.

Figure 2: Software input window

Simulation steps with GasTurb software

The first step in simulation is to select the engine cycle. The cycles available in this software are types of turbojet, turbofan, turboshaft, turboprop, and ramjet, which are selected in accordance with the simulation goals.

The second step is to select the engine design point. In order to simulate the gas turbine, first, it is necessary to select a point as the design point, and then off-design calculations are performed to obtain the characteristics of the engine. In order to perform design point calculations, it is necessary to enter nearly 50 parameters in the software tabs. If high-accuracy analyses are considered (component efficiency calculations or compressor and turbine design), the number of input parameters in this section will increase. It should be noted that before entering the values of the mentioned parameters, the conditions of the design point (in flight mode or when the engine is on the ground) must be specified. These conditions are determined by defining various parameters such as height, temperature difference from the standard state, Mach number, and humidity.

The third step is off-design calculations. Designed gas turbines do not necessarily operate at the operational point of their design for reasons such as power consumption changes (in an industrial gas turbine), changes in thrust (in an air gas turbine), or even changes in environmental conditions. Depending on the changes of performance parameters in such conditions, calculations are performed to extract these changes, called off-design calculations. The

general algorithm of off-design calculations of each set, including gas turbine engines, is based on decomposing them into several components and then defining the behavior of each by calculation or experiment. Then, according to the functional conditions, a series of relationships between thermodynamic, aerodynamic, and geometric parameters are extracted using physical laws, leading to a set of equations. Off-design operating conditions are obtained by solving these equations. It should be noted that the only difference between the different off-design calculations is their methods in solving systems of equations. Finally, graphs or tables are obtained using these calculations that show the different parameters of the engine relative to engine speed or changes in environmental conditions.

Modeling an ALF 502 gas turbine

In order to model an engine in GasTurb software, it is first necessary to select the desired thermodynamic cycle. A twin-spool turbofan with a gearbox with a ratio of 2.3:1 is selected for this research. Therefore, the corresponding thermodynamic cycle in the software is selected and shown in figure 3.
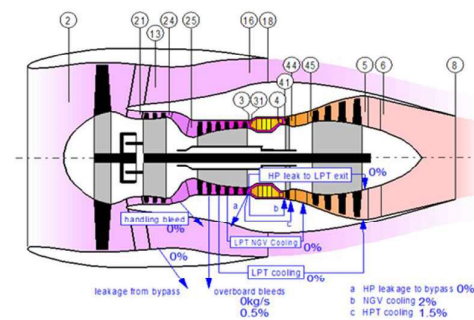

Figure 3: Corresponding cycle with ALF 502 engine in GasTurb software

Since the maximum thrust of an aero-engine is obtained in take-off and the maximum power is intended for aero-derivative industrial engines, the study point was the take-off point. The condition of the engine and its components are examined at this point.

The ALF 502 turbofan engine is modeled using the information available at the take-off point to check the mentioned engine's performance and software performance verification, and the results are presented in Table 2. Also, to validate the process, comparisons were made between the main

parameters of the engine according to the information available for the ALF 502 engine. The results are presented in Table 3. This comparison shows that the modeling performed is relatively consistent with the available data.

Table 2: General specifications of the simulated ALF 502 engine

Mass flow rate to the high-pressure compressor	kg/sec	12.01
Total net thrust	kN	31.49
Special fuel consumption	kg/hr.kN	40.346
Total pressure ratio	-	11.76
Engine core efficiency	%	37.26

Table 3: comparison of the simulated engine with available data of the engine

Parameter	ALF 502 engine	the simulated engine	Error percentage
Total net thrust	31.137	31.49	1.13%
Special fuel consumption	41.4	40.346	2.54%

Off-design calculations of the ALF 502 engine during take-off were performed to evaluate the performance of engine components in different conditions, and the results are presented below. Figures 4 to 6 show the characteristics of the fan, low-pressure and high-pressure compressors, respectively. These figures show the pressure ratio by constant velocity lines in terms of modified mass flow rate. It should be noted that the dashed lines represent the fixed efficiency lines, and yellow square dots also indicate the compressor performance line. The performance curves of high-pressure and low-pressure turbines are also shown in figures 7 and 8, respectively.
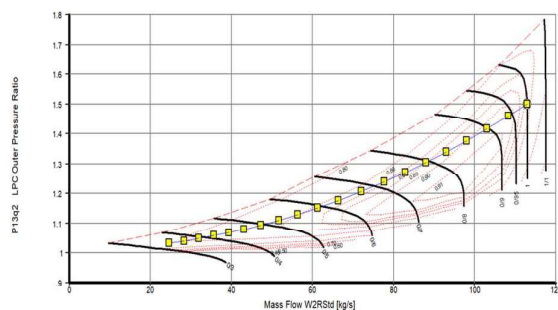

Figure 4: Performance curve of the fan of ALF 502 engine during take-off
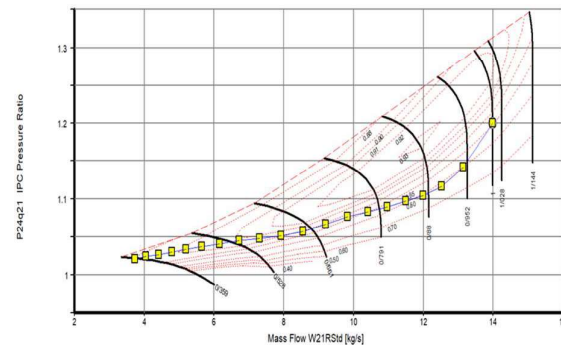

Figure 5: Performance curve of a low-pressure aero-engine compressor during take-off
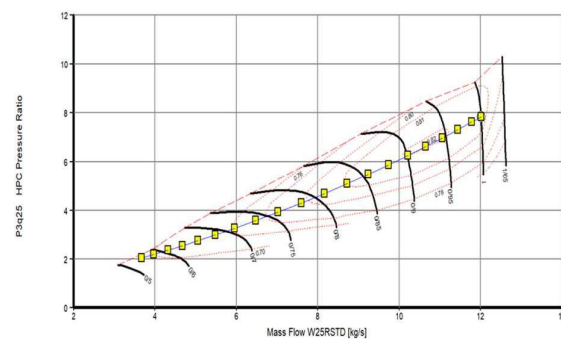

Figure 6: Performance curve of a high-pressure compressor of ALD 502 engine during take-off
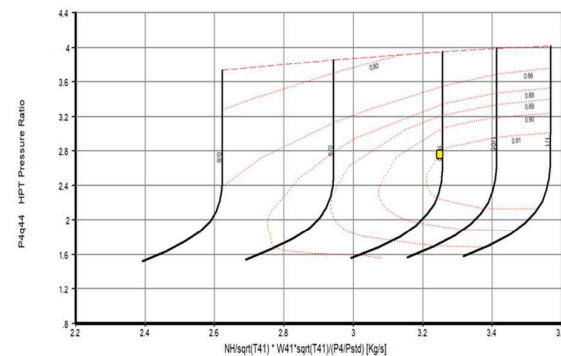

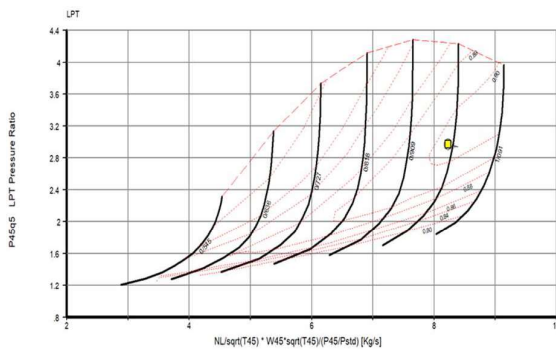**Figure 7:** Performance curve of a high-pressure turbine of ALF 502 engine during take-off

Figure 8: Performance curve of a low-pressure turbine of ALF 502 engine during take-off

Simulation of industrial gas turbines derived from ALF 502 engines

By paying close attention to the aero-derivative gas turbines, it can be seen that various methods have been used to change the use of aero engines to industrial gas turbines. Many factors are involved in choosing methods and their applications, such as the type of need, the ability to build, the type of application. Many of these methods have been implemented on aero engines in this research, and the results have been investigated.

The first step to start the changes is to remove the fan and outlet nozzle of the aero engine. Applying these changes, the engine components are taken out of design mode and placed in a new operating point. Therefore, it is necessary to extract a new operating point specification. After removing the fan and output nozzle, the second step is to achieve a twin-spool or single spool core. In a twin-spool core, the low-pressure and high-pressure spools are maintained after removing the fan and output nozzle, and they are used to generate power. However, in the single spool core, the low-pressure spool is also removed in addition to the fan and output nozzle, and only the high-pressure spool is used to generate power. In the third step, it is necessary to determine how power is transferred from the engine core. This is done in two ways: in the first method, several stages of power turbines are used that are mechanically independent but aerodynamically coupled to the output of the

low-pressure turbine. Another method is a direct connection of the power shaft to the low-pressure spool (twin-spool core) or the high-pressure spool (single-spool core) of the gas generator.

In some cases, several stages of low-pressure compressors have been added to the engine core to compensate for the pressure drop due to fan removal. This is done to increase the power of the derived engine and bring its operating conditions closer to the operating conditions of the design mode. In summary, the mentioned methods can be categorized as follows:

- The derived industrial engine in twin-spool configuration and connection of power shaft to low-pressure spool
- The derived industrial engine in twin-spool configuration and addition of several stages of power turbines
- The derived industrial engine in twin-spool configuration and connection of power shaft to the low-pressure spool along with increasing stages of the low-pressure compressor
- The derived industrial engine in twin-spool configuration and the addition of several stages of power turbine with the addition of stages of the low-pressure compressor
- The derived industrial engine in a single spool configuration and connecting the power shaft to the high-pressure spool
- The derived industrial engine in a single spool configuration and the addition of stages of power turbines

Different scenarios have been studied in GasTurb. It should be noted that natural gas is used as fuel in most industrial engines. Therefore in this study, natural gas is used in aero-derivative industrial engines.

The derived industrial engine in twin-spool configuration and connection of power shaft to low-pressure spool

This industrial gas turbine design type will maintain low- and high-pressure spools. However, input conditions to the low-pressure compressor will change due to fan removal, and consequently,

the operating point of other components also changes. Also, the inlet air will enter the low-pressure compressor by passing through the inlet opening. In this research, the inlet opening efficiency is considered 99%. The power turbine is not used in this engine, and power generation is provided by a direct connection of the power shaft to the low-pressure spool. The configuration used in this software is a twin-spool turboshaft engine, shown in figure 9. The performance parameters obtained from this simulation are presented in table 4. It should be noted that the engine input conditions are standard temperature and pressure.
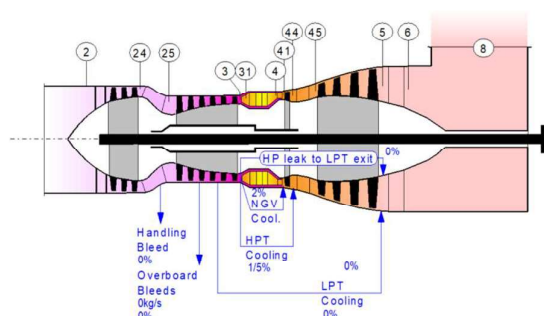

Figure 9: Configuration used in GasTurb software for the first scenario

Table 4: General specifications of the ALF 502 engine simulated in the first scenario

Shaft power	MW	3.400
Outlet temperature from the combustion chamber	K	1304/56
Special fuel consumption	kg/hr.kN	0.2512
Total pressure ratio	-	9.5
Thermal efficiency	%	28/81

The derived industrial engine in a twin-spool configuration and the addition of several stages of power turbines

This model is similar to the previous one in terms of configuration, and the only difference is in its power generation. In the previous model, the power generated by the gas generator was transferred to the consumer by directly connecting the power shaft to the low-pressure spool. However, this model uses several stages of power turbines that are aerodynamically connected to the engine core. It should be noted that the power turbine speed is set to 7350 rpm. Also, the pressure and temperature entering the engine are the same

as the standard pressure and temperature. The software uses a twin-spool turboshaft engine with a power turbine, shown in figure 10. In this scenario, after introducing the performance diagrams to the software, it is observed that the performance diagram of the low-pressure turbine cannot match the other components, and therefore the new operating point is not formed. The implication of this configuration depends on changing the low-pressure turbine. However, the slightest changes are desirable. Therefore, this configuration is rejected.
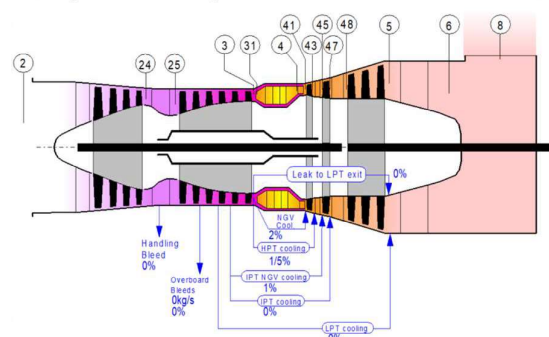

Figure 10: Configuration used in GasTurb software for the second scenario

The derived industrial engine in twin-spool configuration and connection of power shaft to the low-pressure spool along with increasing stages of the low-pressure compressor

This configuration is an upgraded engine configuration presented in Section 1-6. The simulation shown in figure 9 has been used in the software. In this model, as mentioned earlier, one stage of low-pressure compressor is added to the engine core to compensate for the pressure drop due to fan removal. Based on the engine's geometry, the new stage of the low-pressure compressor is considered similar to its first stage. Since the low-pressure compressor had one stage in the original case, it has two stages after adding this new stage. Therefore, they are similar to each other in terms of geometric parameters. The performance parameters of this simulation are presented in table 5. It is worth mentioning that the engine input conditions are standard temperature and pressure.

Table 5: General specifications of ALF 502 engine in the third scenario

Shaft power	MV	4.119
Outlet temperature from the combustion chamber	K	1360.14
Special fuel consumption	kg/hr.kN	0.2440
Total pressure rate	-	10.91
Thermal efficiency	%	29.66

The derived industrial engine in twin-spool configuration and the addition of several stages of power turbine with the addition of stages of the low-pressure compressor

This model is also an upgraded configuration model presented in section 2-6, whose gas generator has been strengthened by adding one stage of compressor to the low-pressure compressor section. Also, the same configuration shown in figure 10 was used to simulate this model in the software. As mentioned in section 2-6, two stages of the power turbine are aerodynamically coupled with the gas generator to transfer the engine output power in this type of configuration. It should be noted that in this model, the power shaft speed is set to 7250 rpm. In this type of configuration, it is observed that after comparing the performance diagrams, the low-pressure turbine cannot adapt to other components, and the performance point is not formed. Similar to the scenario in section 2-6, the use of this type of configuration depends on the change of the low-pressure turbine. However, a few changes are desirable, so this configuration is unacceptable.

The derived industrial engine in a single spool configuration and connecting the power shaft to the high-pressure spool

In this type of design, the industrial gas turbine, fan, outlet nozzle, and the low-pressure spool are removed, and only the high-pressure spool is maintained. The inlet air will also enter the compressor by passing through the inlet opening with 99% efficiency. The configuration used to simulate the performance of the industrial engine is a single spool turboshaft engine consisting of seven stages of the axial compressor and one stage of the radial compressor, run by two stages of the axial turbine. This engine is shown in figure 11. As shown in the figure, no power turbine is used in this type of engine, and the generated power is

supplied by connecting the power shaft directly to the engine core axial. After entering the performance diagrams into the software, it is observed that the characteristic diagram of the turbine cannot adapt to the gas generating compressor, and no new operating point is formed. Therefore, the high-pressure turbine cannot be used in industry. Since using another high-pressure turbine in this model is costly, this scenario is also rejected.
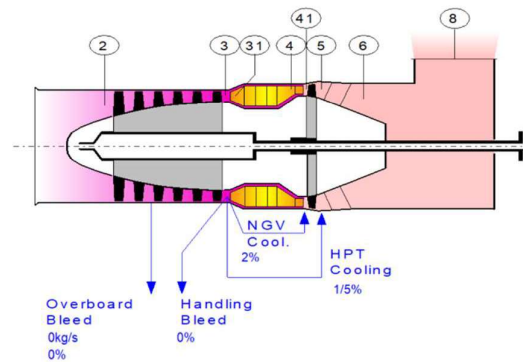

Figure 11: Configuration used in GasTurb software for the fifth scenario

The derived industrial engine in a single spool configuration and the addition of stages of power turbines

This model is also very similar to the previous one in terms of configuration, and the only difference is in their power generation. In the previous model, the generated power was transferred to the consumer by the gas generator through a direct connection of the power shaft to the low-pressure spool. However, in this model, several power turbine stages are aerodynamically connected to the engine core. The model used in the software is a single spool turboshaft engine with a power turbine, shown in figure 12. It should be noted that the shaft speed of the power turbine is set to 7350 rpm. Also, the pressure and temperature entering the engine are the same as the standard pressure and temperature. The performance parameters obtained from this simulation are presented in table 6. It should be noted that the engine input conditions are standard temperature and pressure.
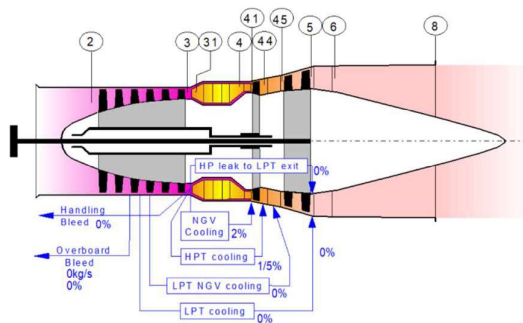
Figure 12: Configuration used in GasTurb software for the sixth scenario

Table 6: General specifications of ALF 502 engine in the third scenario

Shaft power	MW	2.734
Outlet temperature from the combustion chamber	K	1222.33
Special fuel consumption	kg/hr.kN	0.2457
Total pressure rate	-	8.037
Thermal efficiency	%	29.45

Comparison of selected scenarios

In the first scenario, the fan and the outlet nozzle of the aero-engine are removed, and then the output power shaft is connected to the low-pressure spool. As seen in the relevant section, the aero-engine components in the industrial mode are not inconsistent in terms of compatibility and create a new operating point. Due to the direct connection of the power shaft to the gas generator spool, this configuration is recommended in applications that a constant speed is required in the power shaft (such as generators).

In the second scenario, after removing the fan and the output nozzle, a power turbine is used to transfer the power of the industrial engine. The results show that the components of the aero-engine in the industrial mode do not have the necessary compatibility, and the operating point is formed only if another low-pressure turbine replaces the low-pressure turbine of the aero engine. Therefore, according to these conditions, this scenario is costly and is rejected.

In the third scenario, after removing the fan and outlet nozzle, another stage is added to the low-pressure compressor to bring the operating conditions of the industrial engine to the aero engine. The power shaft is directly connected to

the low-pressure spool of the gas generator to enhance the engine power. In this model, the components have no problems in terms of compatibility, and a new functional point is obtained for the industrial application of the engine. It should also be noted that this model, like the first scenario, is recommended for applications where a constant speed is required.

The fourth scenario is the same as the third scenario, except that the aerodynamic coupling of the power turbine with the engine core is used. In this case, as in the second scenario, the components of the aero-engine are incompatible, and a new operating point is not formed without replacing the low-pressure turbine with another model. Therefore, this scenario is also rejected due to technical inefficiency and requires extensive changes.

In the fifth scenario, the low-pressure spool, fan, and output nozzle are also removed, and the power shaft is connected directly to the low-pressure spool of the core. In this new configuration, the compressor and the high-pressure turbine do not have the necessary compatibility. On the other hand, forming a new operating point depends on replacing the high-pressure turbine with another high-pressure turbine with a relatively high-pressure ratio. Therefore, since fewer changes are desirable, this scenario is also rejected.

In the sixth scenario, the changes are similar to the fifth scenario, except that the power turbine is aerodynamically coupled with the engine core to transfer the generated power. In this case, the compressor and the relevant turbine have the necessary compatibility, and a new operating point is formed in industrial use. Despite having less Shaft power in this scenario than other scenarios, it can be used in variable cycles. This relates to the fact that fewer changes are required in this model, and it is more similar to the turboshaft T55 (ALF 502 engine). As it has broader applications, it is more desirable.

Therefore, among the existing scenarios, the first, third, and sixth scenarios can be implemented in ALF 502 engine in accordance with the required type of application. Figures 13, 14, and 15 compare Shaft power values, specific fuel consumption, and thermal efficiency for these selected scenarios, respectively.
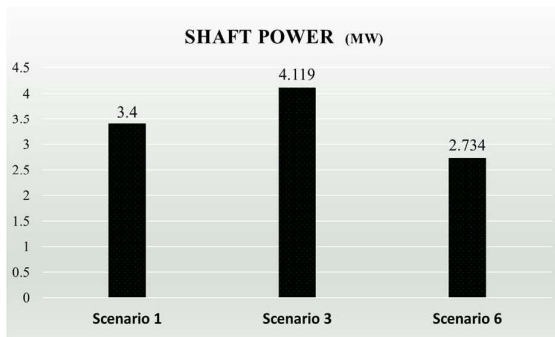
SHAFT POWER (MW)

Figure 13: Comparison of shaft power in selected scenarios

SFC (KG/KW.HR)
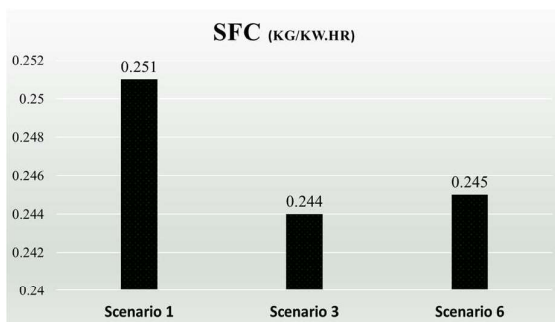
Figure 14: Comparison of specific fuel consumption in selected scenarios
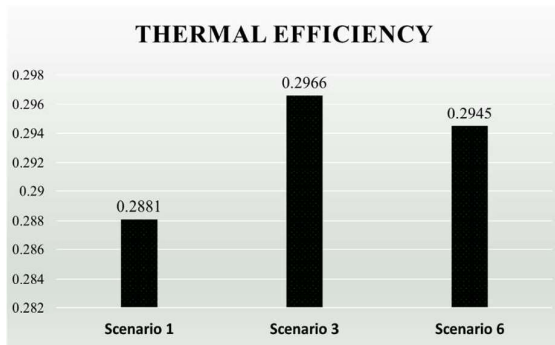
THERMAL EFFICIENCY

Figure 15: Comparison of thermal efficiency in selected scenarios

Summary and conclusion

One of the ways to reduce the cost of manufacturing industrial gas turbines is to use aero engines and turn them into industrial gas turbines. For this purpose, the aero-engine gas generator is used as the industrial gas turbine core. In addition, in cases where the aero engines cannot obtain flight permits, this technology, to some extent, can compensate the capital of companies.

In the present work, an attempt has been made to study the existing scenarios for this change on the ALF 502 turbofan engine using GasTurb software

and select the ideal scenario. Initially, the aero-engine was modeled at the design and off-design point conditions, and the results were validated with existing data. Then, using the diagram of the characteristics of aero-engine components, the scenarios for achieving the industrial engine are modeled using the software, and the results are compared with each other. Among the mentioned scenarios, three did not have the necessary efficiency and were rejected for various reasons. Among the remaining three scenarios, two are related to direct connection configurations recommended for applications with fixed output speed. One scenario is related to the power turbine configuration suitable for applications with variable output speed. Given that in the last scenario, fewer changes are needed, it has broader applications and is more similar to the initial core configuration (T55 engine). Therefore, this is selected as the ideal scenario.

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