International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

Component Sizing and Design-Point Performance Evaluation of a Two-Spool Turbofan Engine with Mixed Exhaust and Afterburner

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Abstract: ***This paper presents a simplified design-point sizing methodology for a two-spool turbofan engine with mixed exhaust, including an afterburning configuration. The high-pressure (HP) turbine drives the HP compressor, and the low-pressure (LP) turbine drives the fan. Three configurations are analyzed: (i) mixed-exhaust turbofan with afterburner and fuel injection, (ii) mixed-exhaust turbofan with afterburner but without fuel injection, and (iii) mixed-exhaust turbofan without afterburner. Using specified cruise Mach number and altitude, design thrust, turbine inlet temperature, component pressure ratios/efficiencies, spool speeds, and combustor/afterburner pressure losses, a component-matching procedure is implemented in C to compute stagnation states, mass flow rate, and required flow areas for each component. Compressor and turbine characteristic maps from the Gas Turbine Simulation Program (GSP-10) are used as reference maps; size ratios are obtained by equating non-dimensional mass flow so that the maps can be applied to the new design. The predicted thrust and thrust specific fuel consumption (TSFC) agree with GSP-10 within approximately 4% and 12%, respectively, for the tested design point. For the studied case, afterburning increases thrust by about 105% at the expense of roughly 309% increase in fuel flow, supporting the practical use of afterburning only for short duration thrust augmentation.***

Keywords: Turbofan engine; component sizing; design-point performance; component matching; afterburner; GSP-10 validation

Nomenclature

Symbol	Description
B	Bypass ratio
C	Flow velocity (m/s)
c_p	Specific heat at constant pressure (kJ/kg-K)
M	Mach number
P, P0	Static and stagnation pressure
T, T0	Static and stagnation temperature
η γ	Efficiency Gamma
$\dot{m}$ Rp	Mass flow rate (kg/s) Pressure Ratio
TSFC	Thrust specific fuel consumption (kg/N·h)

1. Introduction

Gas-turbine engines are widely used for aircraft propulsion and stationary power generation. At the preliminary design stage, it is often useful to have a transparent physics-based sizing tool that computes component flow areas and cycle performance from a consistent set of assumptions and component-matching constraints, instead of relying exclusively on closed commercial software. Similar model-based design and validation workflows are common in other mechanical systems, including conceptual design and finite-element-based evaluation of complex multi-DOF machines [1-4].

The thermodynamic relations typically used for one-dimensional component-based cycle calculations, as well as practical considerations in compressor/fan and turbine modelling, are well documented in standard gas-turbine and propulsion texts [5-7]. In industry and academia, map-based simulation environments such as the Gas Turbine Simulation Program (GSP) and GasTurb are frequently used for design and off-design performance evaluation [8,9].

Several studies have reported component sizing and matching methodologies for turbofan and gas-turbine engines, including two-spool configurations and off-design considerations [10-14]. Off-design compressor map behavior and diagnostics-oriented modelling have also been widely discussed in the literature [15-17]. Motivated by these references, the present work develops a numerical methodology for design-point analysis of a two-spool turbofan engine with mixed exhaust and optional afterburning and validates the results against a corresponding GSP-10 reference model [18].

2. Engine Configuration and Design-Point Inputs

The analyzed engine is a two-spool turbofan with mixed exhaust. The diffuser delivers freestream air to the fan and core compressor. The HP turbine drives the HP compressor, and the LP turbine drives the fan. An afterburner may be placed downstream of the mixer.

Three cases are considered:
1) Mixed-exhaust turbofan with afterburner and fuel injection,
2) Mixed-exhaust turbofan with afterburner without fuel injection, and
3) Mixed-exhaust turbofan without afterburner.

The design point is defined by cruise Mach number and altitude, required thrust, turbine inlet temperature, component pressure ratios and efficiencies, spool speeds, combustor pressure loss, mixer pressure ratio, and (when applicable) afterburner exit temperature and pressure loss. The bypass ratio used in the study is B = 0.9. The general layout of a Turbofan Engine with mixed exhaust and afterburner is depicted in Figure 1. The GSP-10 model of the same engine is shown in Figure 2.

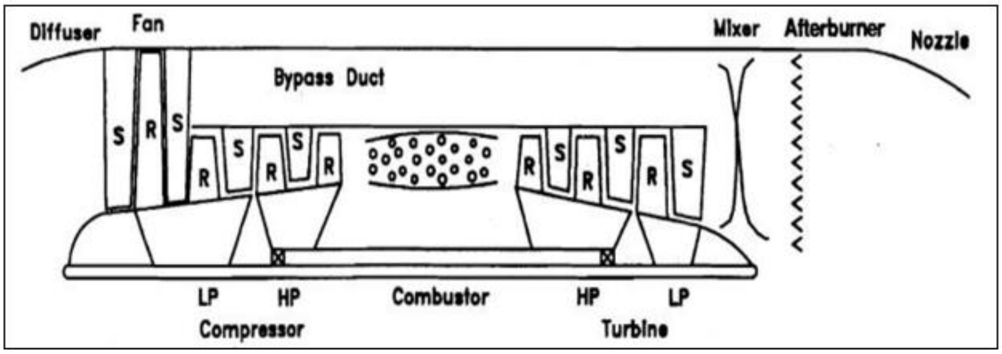

Figure 1: Turbofan Engine with mixed exhaust and afterburner

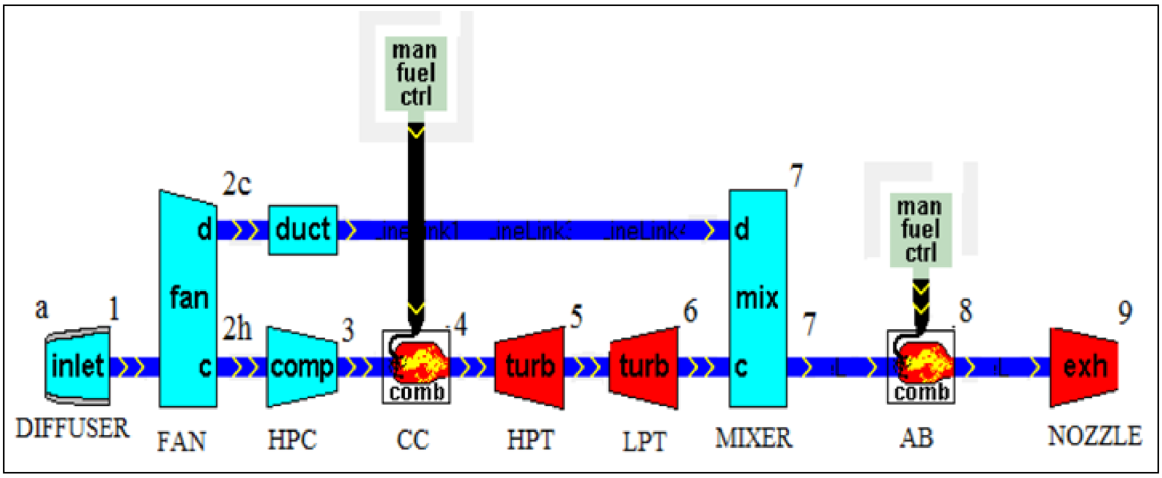

Figure 2: GSP-10 model of Turbofan Engine with mixed exhaust and afterburner

3. Numerical Methodology

The design-point model computes stagnation properties across each component using standard one-dimensional steady-flow relations. Work compatibility is enforced between turbomachinery on the same spool, and flow compatibility is enforced at each station using continuity and matched non-dimensional mass flow. Representative governing relations are listed below (subscripts follow the station numbering used in the component schematic). The underlying one-dimensional relations follow standard gas-turbine performance formulations [5-7,18].

(1) $T0a = Ta\,[1 + (\gamma_a - 1)/2 \cdot M_a^2]$

(2) $P0a/Pa = (T0a/Ta)^{\wedge}(\gamma_a/(\gamma_a - 1))$

(3) $P01 = Pa\,[1 + \eta_d\,(\gamma_a - 1)/2 \cdot M_a^2]^{\wedge}(\gamma_a/(\gamma_a - 1))$

(4) $P02 = P01 \cdot (Rp,f)$, $T02 = T01\,[1 + ((Rp,f)^{\wedge}((\gamma_a - 1)/\gamma_a) - 1)/\eta_f]$

(5) $P03 = P02 \cdot (Rp,hpc)$, $T03 = T02\,[1 + ((Rp,hpc)^{\wedge}((\gamma_a - 1)/\gamma_a) - 1)/\eta_c]$

(6) $P04 = (1 - \Delta Pcc) \cdot P03$

(7) Turbine temperature drops from spool work balance; for the HP spool:

$cp_g\,(T04 - T05)\,\eta_m = 1.1 \cdot cp_a\,(T03 - T02)$

(8) Mixer exit stagnation temperature by enthalpy balance:

$T07 = [B \cdot cpa \cdot T02 + cp_g \cdot T06] / [(B+1) \cdot cp_m]$

(9) Afterburner pressure loss: $P08 = (1 - \Delta P_{ab}) \cdot P07$; afterburner exit temperature is specified for the fuel-injected case.

The nozzle condition (choked/unchoked) is determined using the critical pressure ratio and nozzle efficiency. After the overall mass flow rate is computed from the specific thrust, component inlet areas are obtained from the continuity equation at each station.

4. Component-map scaling and validation against GSP-10

Compressor and turbine characteristic maps from GSP-10 are adopted as reference maps for a standard-size machine. To use these maps for the present design, component size ratios are computed such that the non-dimensional mass flow matches between the new design and the reference component at the design point. The developed C code then solves the coupled matching problem and produces design-point performance and station properties. Validation is performed by running the corresponding GSP-10 model at the same design-point inputs and comparing outputs. The use of reference component maps and scaled non-dimensional flow is consistent with common practice in map-based performance tools [8,9,15].

5. Results

Tables 1–3 compare the developed model with the GSP-10 results for the three configurations. (Pressures are in kPa and temperatures in K as used in the original GSP tables.)

Table 1: Case (i) - with afterburner and fuel injection.

Variable	Present model	GSP-10
Mass flow rate, ṁ (kg/s)	12.176	12.176
T01	244.381	244.381
P01	33.149	33.147
T02 (hot)	376.505	389.84
T02 (cold)	376.505	391.91
P02 (hot)	132.595	132.586
P02 (cold)	132.595	132.586
T03	693.866	704.87
P03	818.113	818.056
P04	785.388	785.334
Thrust (kN)	**10.824**	**10.363**
TSFC (kg/N·h)	**0.2165**	**0.2457**

Table 2: Case (ii) - afterburner hardware without fuel injection.

Variable	Present model	GSP-10
Mass flow rate, ṁ (kg/s)	25.061	25.061
T01	244.381	244.381
P01	33.149	33.147
T02 (hot)	376.505	389.84
T02 (cold)	376.505	391.91
P02 (hot)	132.595	132.586
P02 (cold)	132.595	132.586
T03	693.866	704.87
P03	818.113	818.056
P04	785.388	785.334
Thrust (kN)	10.824	9.568
TSFC (kg/N·h)	0.1087	0.0988

Table 3: Case (iii) - mixed exhaust without afterburner.

Variable	Present model	GSP-10
Mass flow rate, ṁ (kg/s)	24.520	24.520
T01	244.381	244.381
P01	33.149	33.147
T02 (hot)	376.505	392.59
T02 (cold)	376.505	396.37
P02 (hot)	132.595	132.586
P02 (cold)	132.595	132.586
T03	514.381	533.33
P03	328.836	328.813
P04	815.514	815.457
Thrust (kN)	10.824	10.759
TSFC	0.1052	0.1032

6. Discussion

The developed model reproduces the design-point trends of the reference GSP-10 model, with the largest deviations observed in temperatures downstream of the fan and compressors. These differences are expected because the present implementation adopts simplified one-dimensional relations and assumes fixed component efficiencies, while GSP-10 employs detailed component-map interpolation and internal loss models. Despite these simplifications, the agreement in thrust and TSFC is acceptable for preliminary design and classroom use. The afterburner case shows the expected trade-off: large thrust augmentation at a disproportionately high fuel-flow penalty, supporting operational use only when short-duration thrust boost is required. Similar sources describe the impact of detailed loss models and map interpolation on predicted station temperatures and fuel consumption [15,18].

7. Conclusions

- A design-point sizing and performance tool for a two-spool turbofan engine with mixed exhaust and optional afterburning has been implemented in C using component-matching constraints.
- The tool uses scaled compressor/turbine maps from GSP-10 and computes station properties and component flow areas at the design point.
- Against the corresponding GSP-10 models, thrust and TSFC predictions agree within approximately 4% and 12%, respectively, for the tested design point.
- For the studied configuration, afterburning increases thrust by ~105% at the expense of ~309% increase in fuel flow, indicating that afterburning should be reserved for short duration thrust augmentation.

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