Thermo-Gasdynamic Modeling and Transient-Response Analysis of The Pt6A Engine Operating With Jet A-1 And TS-1

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Abstract**—**This paper presents a zero-dimensional thermo-gasdynamic model for simulating the steady-state and transient response of the PT6A turboprop engine when operating with Jet A-1, TS-1, and assumed blends of these two fuels. The model is updated according to a compressor configuration consisting of four axial-compressor stages and one centrifugal-compressor stage. The conservation equations of mass, energy, and angular momentum are applied to individual engine components, including the inlet, compressor assembly, combustor, compressor turbine, and free turbine. The lower heating value of the fuel is introduced directly into the combustor energy-balance equation to investigate the influence of fuel variation on the combustor-exit temperature, compressor pressure ratio, compressor outlet pressure, propeller speed, and propeller-shaft power. Reduced simulation results for five fuel cases, ranging from 100% Jet A-1 to 100% TS-1, show that the thermodynamic differences are small because both fuels belong to the kerosene family and have similar lower heating values. As the TS-1 fraction increases from 0% to 100%, the peak T3 temperature decreases from 1239.52 K to 1234.70 K, the compressor outlet pressure decreases from 787.16 kPa to 785.41 kPa, and the propeller-shaft power decreases from 562.24 kW to 560.27 kW. All cases maintain the peak T3 temperature below the 1300 K limit in the current model. The results indicate that TS-1 can be evaluated as an alternative fuel with a limited influence on the system-level response of the PT6A engine; however, the final quantitative conclusion must be verified using experimental data and actual fuel properties for each fuel batch.

Keywords**—**PT6A; Jet A-1; TS-1; TC-1; zero-dimensional thermo-gasdynamic model; Matlab-Simulink; transient response; propeller-shaft efficiency.

I. INTRODUCTION

The PT6A engine is a free-turbine turboprop engine widely used in aviation because of its high reliability, simple architecture, and stable operation across a wide range of operating modes and flight conditions. From an energy-conversion perspective, the engine converts the chemical energy of the fuel into heat in the combustor and then into mechanical work through the compressor-turbine and free-turbine stages. In the PT6A, useful power for the propeller is extracted from the free turbine through the propeller shaft and reduction gearbox; this shaft is mechanically independent from the compressor-turbine shaft.

Under operating conditions in Vietnam, Jet A-1 and TS-1 are two kerosene-based aviation fuels of practical importance. Because of the need to ensure fuel logistics, assessing the capability of the engine to operate with TS-1 or Jet A-1 is necessary. Direct testing on a real engine is usually costly and involves the risk of exceeding thermo-structural limits, especially during transient regimes such as start-up, throttle acceleration, or off-design operation. Therefore, a zero-dimensional thermo-gasdynamic model is an appropriate tool for preliminary trend assessment before conducting real-engine tests.

The objective of this paper is to formulate and present a zero-dimensional model for the PT6A engine with a compressor configuration comprising four axial-compressor stages and one centrifugal-compressor stage, to compare Jet A-1 and TS-1 fuels, and to analyze transient simulation results using key indicators such as combustor-exit temperature, compressor pressure ratio, compressor outlet pressure, propeller-shaft speed, propeller-shaft power, and thermal efficiency based on propeller-shaft power.

II. MODEL BASIS AND CALCULATION METHOD

A. Engine Structure and Modeling Assumptions

The model is developed using a zero-dimensional approach, in which each engine component is represented by spatially averaged variables. The gas-flow path is described as a sequence consisting of the inlet, four axial-compressor stages, one centrifugal-compressor stage, the combustor, the compressor turbine, the free turbine, and the exhaust. This approach does not describe the detailed three-dimensional flow field or the fuel-injection process, but it enables fast system-level response calculations and comparisons among different fuels.

The compressor assembly is modified to include four axial-compressor stages and one centrifugal-compressor stage. In the reduced model, the overall compressor pressure ratio is kept close to the reference value, while the pressure ratio of each axial stage is distributed non-uniformly to reflect the progressive pressure rise across multiple stages. The centrifugal stage still provides the main pressure increase upstream of the combustor.

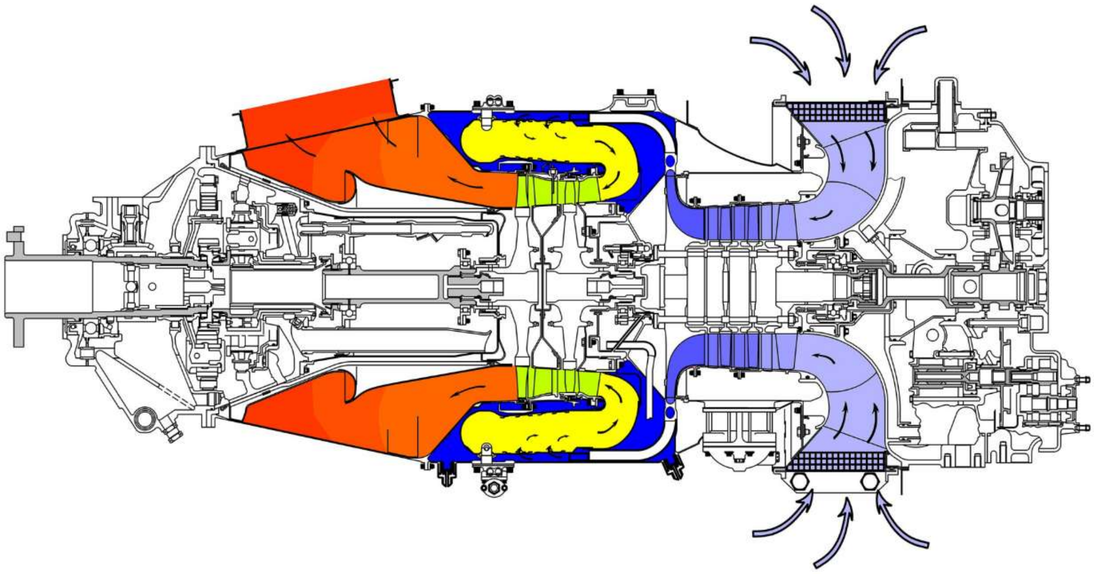

Fig. 1. Structural diagram of the PT6A engine.

Modeling assumptions:

TABLE I. DISTRIBUTION OF PRESSURE RATIO IN THE PT6A COMPRESSOR

Component	Pressure ratio	Role in the model
Axial-compressor stage 1	1.3576	Primary pressure rise downstream of the inlet
Axial-compressor stage 2	1.3380	Further increase in pressure and temperature
Axial-compressor stage 3	1.3225	Intermediate pressure rise
Axial-compressor stage 4	1.3072	Completion of the axial-compression section
Centrifugal-compressor stage	2.4741	Main pressure rise upstream of the combustor
Total compressor assembly	7.7687	Overall compressor pressure ratio

B. Fuel Properties and Blending Ratio

The fuel is characterized mainly by its lower heating value (LHV). In the current model, Jet A-1 has an LHV of 42.8 MJ/kg and TS-1 has an LHV of 42.5 MJ/kg. For a mass-based fuel mixture, the effective heating value is calculated using the mass-weighted average rule:

$$LHV\_mix = (1 - x\_TS1)\ LHV\_JetA1 + x\_TS1\ LHV\_TS1$$

where x_TS1 is the mass fraction of TS-1 in the mixture. The simulation matrix includes five cases: 100% Jet A-1; 75% Jet A-1 + 25% TS-1; 50% Jet A-1 + 50% TS-1; 25% Jet A-1 + 75% TS-1; and 100% TS-1.

C. Main Evaluation Equations

A reduced combustor energy-balance equation is used to calculate the evolution of temperature T3:

$$rho\ V\_B\ c\_p\ dT3/dt = m\_dot\_a\ c\_p\ (T2 - T3) + m\_dot\_f\ (LHV - c\_p\ T3)$$

The overall compressor pressure ratio is determined from the compressor outlet pressure and inlet pressure:

$$pi\_c = p2 / p1$$

An approximate Brayton efficiency is used to monitor the trend of thermal energy conversion in the cycle:

$$eta\_b = 1 - (T4 - T\_atm) / (T3 - T2)$$

The propeller-shaft power efficiency is the ratio between the useful power on the propeller shaft generated by the free turbine and the thermal power supplied by the fuel:

$$eta\_p = P\_shaft / (m\_dot\_f\ LHV) = (omega\_p\ M\_l) / (m\_dot\_f\ LHV)$$

In the above expression, omega_p is the angular speed of the propeller shaft, and M_l is the propeller load torque.

TABLE II. SYMBOLS AND MEANINGS OF THE MODEL VARIABLES

Symbol	Meaning
N_FT	Free-turbine speed upstream of the reduction gearbox
N_prop	Propeller-shaft speed downstream of the reduction gearbox
i_g	Reduction-gearbox ratio
omega_prop	Angular speed of the propeller shaft
M_prop	Load torque at the propeller shaft
P_prop	Mechanical power at the propeller shaft
m_dot_f	Fuel mass-flow rate
LHV	Lower heating value of the fuel
eta_prop	Thermal efficiency based on propeller-shaft power
pi_c	Overall compressor pressure ratio
T3	Combustor-exit / turbine-inlet gas temperature

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III. SIMULATION SETUP

The fuel cases include 100% Jet A-1; 75% Jet A-1 + 25% TS-1; 50% Jet A-1 + 50% TS-1; 25% Jet A-1 + 75% TS-1; and 100% TS-1. In the reduced simulation, the LHV of Jet A-1 is set to 42.8 MJ/kg and the LHV of TS-1 is set to 42.5 MJ/kg. These values should be replaced by fuel-test certificate data when applying the model to actual fuel batches.

TABLE III. SIMULATION PARAMETERS

Simulation parameter	Value
Free-turbine speed	30,000 rpm
Propeller-shaft speed downstream of gearbox	2,000 rpm
Reduction-gearbox ratio	15:1
Assumed gearbox efficiency	0.97
Load torque at propeller shaft	2,684.51 N.m
Nominal fuel mass-flow rate	0.062 kg/s

IV. RESULTS AND DISCUSSION

A. Summary of Results

TABLE IV. RESULTS OBTAINED FROM MATLAB

Fuel	LHV (MJ/kg)	Free-turbine speed (rpm)	Propeller speed (rpm)	Free-turbine torque (N.m)	T3 max (K)	Final T3 (K)	Final p2 (kPa)	Final pi_c	Propeller-shaft power (kW)	Propeller-shaft efficiency
100% Jet A-1	42.80	30,000.0	2,000.0	184.50	1,239.52	1,226.37	787.16	7.77	562.24	0.2167
75% Jet A-1 + 25% TS-1	42.73	29,973.7	1,998.2	184.50	1,238.31	1,225.19	786.73	7.76	561.75	0.2169
50% Jet A-1 + 50% TS-1	42.65	29,947.4	1,996.5	184.50	1,237.11	1,224.01	786.29	7.76	561.26	0.2171
25% Jet A-1 + 75% TS-1	42.58	29,921.0	1,994.7	184.50	1,235.91	1,222.83	785.85	7.76	560.76	0.2173
100% TS-1	42.50	29,894.7	1,993.0	184.50	1,234.70	1,221.65	785.41	7.75	560.27	0.2175

B. Comments on the Graphs

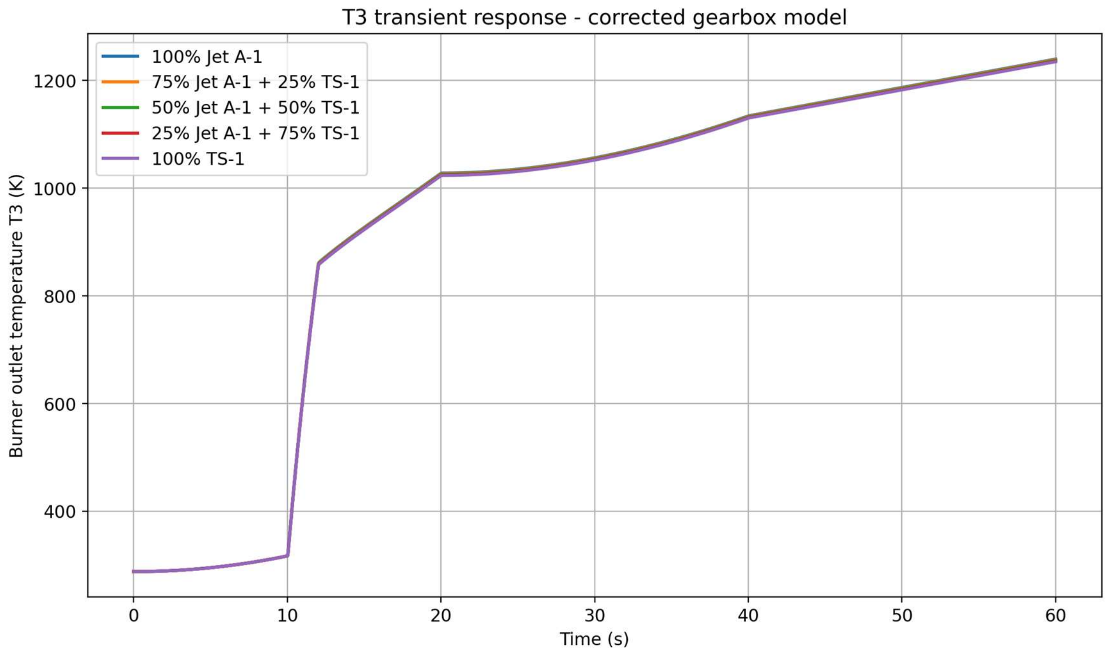

Fig. 2. T3 temperature for the five fuel cases.

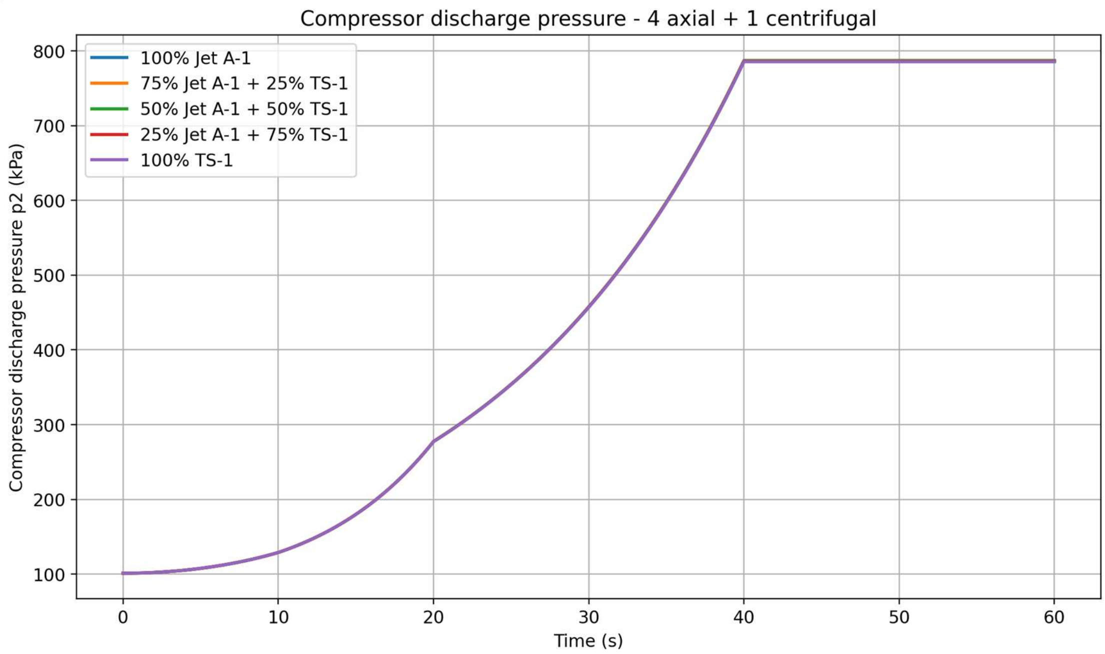

Fig. 3. Compressor outlet pressure p2 for the five fuel cases.

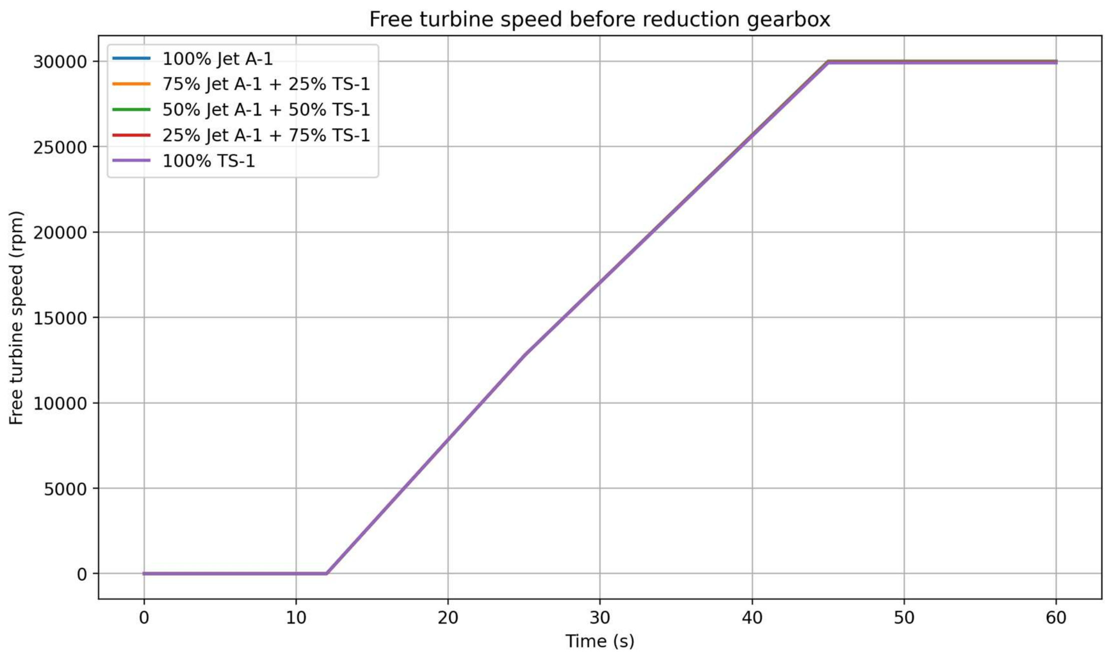

Fig. 4. Free-turbine speed upstream of the reduction gearbox for the five fuel cases.

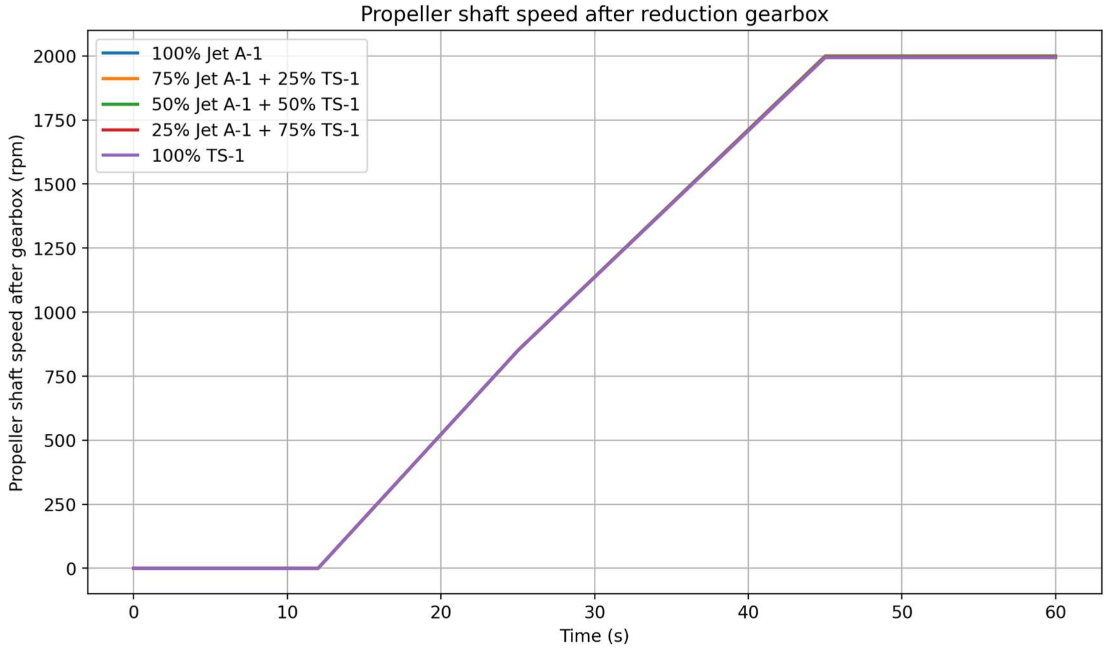

Fig. 5. Propeller-shaft speed downstream of the reduction gearbox for the five fuel cases.

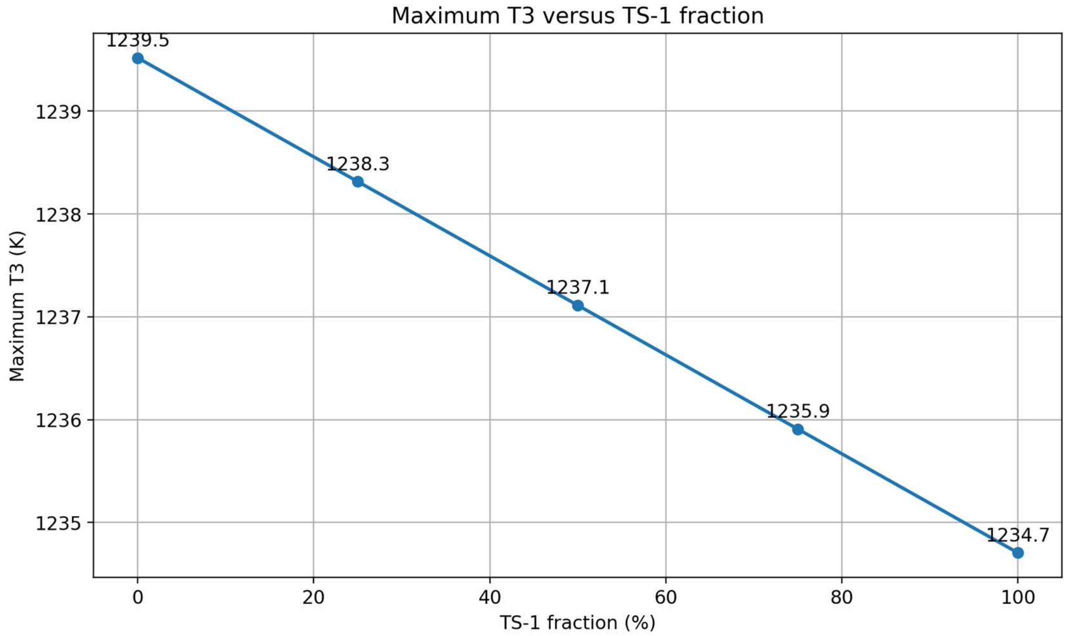

Fig. 6. Peak T3 temperature when using TS-1 fuel.

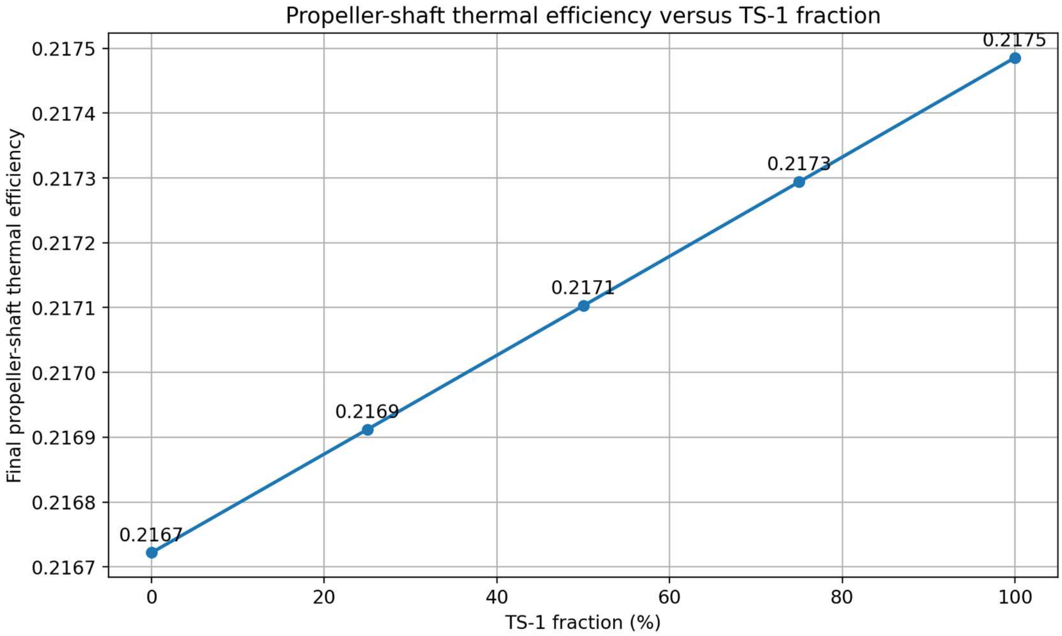

Fig. 7. Propeller-shaft power efficiency when using TS-1 fuel.

The T3 temperature curves show that the difference between Jet A-1 and TS-1 is small under the assumed condition that their LHVs are close. The peak T3 temperature decreases slightly as the TS-1 fraction increases, reflecting the slight reduction in thermal energy supplied to the combustor when the same fuel mass-flow rate is maintained. The p2 pressure curves show only minor variation because the model uses the same compressor configuration and compressor-shaft speed for all fuel cases. This tendency is reasonable when comparing two kerosene-based fuels with similar heating values.

The speed curves show that the free turbine operates around 30,000 rpm, while the propeller shaft downstream of the reduction gearbox operates around 2,000 rpm. This is an important distinction compared with the previous version of the model. Power and efficiency must be calculated based on the propeller shaft downstream of the reduction gearbox, or converted through the gearbox efficiency, and the free-turbine speed must not be confused with the propeller speed.

V. CONCLUSIONS

The paper has been revised to represent correctly the power-transmission chain of the PT6A engine: the free turbine rotates at approximately 30,000 rpm, the power is transmitted through a 15:1 reduction gearbox, and the propeller-shaft speed downstream of the gearbox is approximately 2,000 rpm.

The compressor assembly in the model has been updated to include four axial-compressor stages and one centrifugal-compressor stage. The overall pressure ratio is distributed across the stages while remaining close to the reference value of the system model.

The propeller-shaft power efficiency is calculated as the mechanical power at the propeller shaft downstream of the reduction gearbox divided by the thermal power supplied by the fuel.

Simulation results for Jet A-1 and TS-1 show small thermodynamic differences because the assumed LHVs of the two fuels are close. The peak T3 temperature decreases slightly as the TS-1 fraction increases, while p2 pressure and the compressor pressure ratio vary only slightly.

With a load torque of 2,684.51 N.m and a propeller-shaft speed of 2,000 rpm, the nominal propeller-shaft power for Jet A-1 is approximately 562 kW. If the objective is to reproduce the rated power of a specific PT6A variant, the load torque or fuel-governing law must be adjusted accordingly.

The current model is a reduced zero-dimensional model suitable for trend analysis and for establishing a Matlab-Simulink simulation framework. To draw a quantitative conclusion on the feasibility of replacing Jet A-1 with TS-1, fuel-test data, compressor and turbine maps, and experimental engine-test data for the actual engine configuration must be added.

VI. LIMITATIONS AND FUTURE WORK

The model has not yet described the propeller governor, fuel-control unit, detailed inter-turbine temperature (ITT) limits, combustion efficiency dependence on fuel atomization properties, or thermo-structural interactions. Future work should couple the zero-dimensional model with a fuel-control system, use real compressor and turbine maps, include gearbox efficiency in the dynamic model, and calibrate the model using test data from a specific PT6A configuration.

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