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A Simple Thermal Model of Fuel Thermal Management System in Aircraft Engine

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Abstract

The architecture of the Fuel Thermal Management System (FTMS) in a commercial aircraft engine was built to model and simulate the fuel system. The study shows the thermal interactions between the fuel and engine lubrication oil through the mission profile of a high bypass ratio, two-spool turbofan engine. Fuel temperature was monitored as it flowed through each sub-component of the fuel system during the mission. The heat load in the fuel system strongly depended on the fuel flow rate, and was significantly increased for the periods of cruise and descent with decrease of fuel flow rate, rather than for the periods of take-off. Due to the thermal interaction in the pump housing, the fuel temperature at the outlet of the low-pressure pump was increased (4.0, 9.2, and 30.0) % over the case without thermal interaction for take-off, cruise, and descent, respectively.

Key Words : Fuel Thermal Management System(FTMS), Fuel-Cooled Oil Cooler(FCOC)

1. Introduction

Future aerial vehicles for transportation and reconnaissance have to meet continuous demand for improving its efficiency and long endurance. As a typical effort, saving weights applying light composite materials for airframe structure is more widely implemented. More electric subsystems and devices are installed for advanced aircraft control and also for the needs for passengers.

For reconnaissance, the further requirements for long endurance and stealth drive the demands for the compactness of subsystems. Hence, it means compact but powerful engine fits into the aerial vehicle. To achieve this, minimum core diameter and higher shaft speed are necessary. The increased shaft speed will results higher oil temperature and requires advanced heat management system.

Overall, the requirements for future thermal(heat) management system is getting more complicated and it needs system level approach. In order to mitigate these thermal challenges, system level thermal management is being investigated[1, 2].

An integrated thermal management model enables the prediction of overall system performance and the optimization of thermal management system in the early stage of an aircraft design. The subsystems of an aircraft are often designed and optimized without consideration of vehicle-level interactions among other subsystems. System level analysis considering subsystem interactions could result in significant performance gains across the aircraft, potentially improving the overall effectiveness of future platforms[3-5]. The development of a Modeling and simulation tool allows these performance gains to be quantified[5-9]. Tip-to-Tail model is divided into five subsystems: AVS(Aircraft Vehicle System), Engine, APTMS(Adaptive Power and Thermal Management

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System), FTMS(Fuel Thermal Management System), HPEAS(High Power Electric Actuation System) and REPS(Robust Electrical Power System)[10, 11]. Figure 1 illustrates the required subsystems to build an integrated system level model for thermal management.

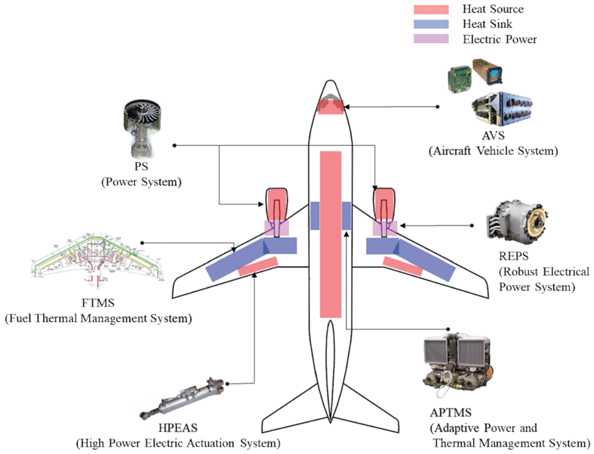

Fig. 1 Architecture of Typical Transport Aircraft

Wolff et al.(2010) has identified the need for an integrated thermal management system analysis. Future aircraft requires three to five times the heat load of legacy platforms while being limited in the ability to reject heat to the environment. Rejecting heat to the engine cycle through various flow paths has become the preferred approach. The added heat load is the result of modern avionics, advanced mission systems, hydraulic vectored thrust control systems, and more electric aircraft engine accessories. Modeling and simulation of the integrated thermal and electrical aircraft systems was a critical part of the INVENT program[3, 12].

The larger thermal loads reduce the propulsion system efficiency by demanding bleed air from the main engine compressor or imposing a shaft load on the high or low pressure shaft. The approach adopted to power the thermal management system influences the overall fuel burn of the aircraft for a given mission[10, 13].

Figure 2 shows the schematics of system level thermal management model and contains information of interactions between subsystems such as signal, fuel, air, electrical power, heat sink and heat source. In the model, fuel of FTMS and cooling air of APTMS are used as a heat sink. APTMS contains air cycle and vapor cycle that cools heat source through cooling air. AVS have information of mission profile and command to PS and FTMS for the required thrust and fuel flow rate.

The present study focuses on investigating the characteristics of fuel temperature through thermal interaction between fuel and engine lubrication oil in FTMS. A Thermal interaction between low pressure pump and high pressure pump also investigated.

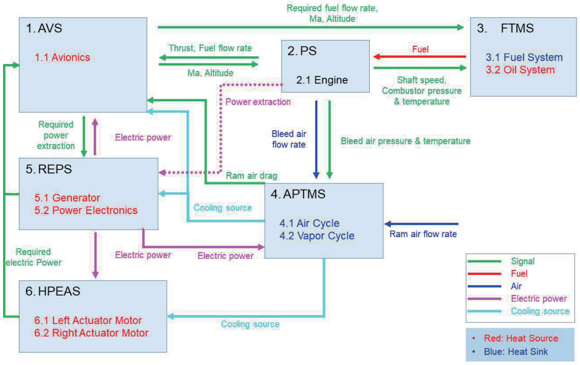

Fig. 2 Block Diagram of an Integrated System Level Model for Thermal Management

2. FUEL SYSTEM AND MODELING OF FUEL THERMAL MANAGEMENT SYSTEM

A fuel system consists of low and high pressure circuits. Fuel is provided from the aircraft fuel tank to the low pressure pump. The low pressure pump simply delivers fuel to the high pressure pump in which sufficient pressure and flowrate will be generated in fuel flow to satisfy the engine demand. Fuel Cooled Oil Cooler(FCOC) transfer heat between oil system and fuel system[15, 16]. Figure 3 represent a typical schematic of FTMS[17, 18].

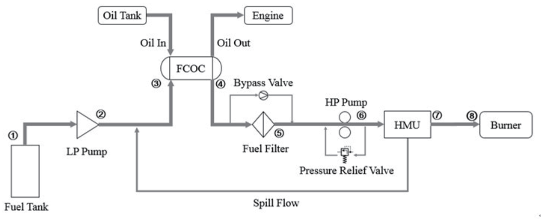

Fig. 3 Schematics of Fuel System

Fuel system modeling in AMESim is shown in Fig. 4. The inlet temperature and pressure were given at each flight condition. Fuel flowrate was controlled by AVS while keeping the constant pressure difference at metering valve. The engine fuel flow demand is proportional to power. Since the high pressure pump is operated by the engine shaft, it may result to deliver excess flowrate. This surplus fuel is spilled back into the low pressure fuel system. In this case, if fuel flow rate is small, it may result in a significant fuel temperature rise.

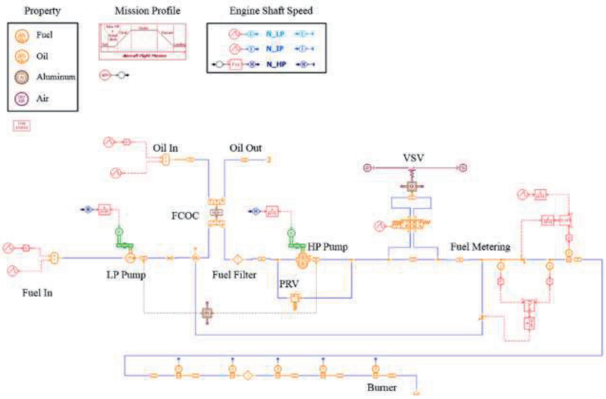

Fig. 4 The Modeling of Fuel Thermal Management System using AMESim

2.1 Fuel Pumps

The purpose of the low pressure centrifugal pump is to maintain the fuel pressure for the high pressure pump. The high pressure pump which is typically a gear type is used to raise the pressure of the fuel. It provides sufficient fuel flow at pressure over all engine speeds and operating conditions. Gear pump is a constant displacement pump: for each revolution, a fixed volume of fuel is delivered equivalent to the gear tooth volume; therefore, the volume of flow delivered per revolution is constant. The output pressure is dependent on the back pressure, which is the sum of all downstream unit pressure losses plus the combustor internal pressure.

The pump models are defined as functions of flow rate and pressure ratio. The efficiency is used to determine the actual work rate. The pump speed is directly related to engine speed through a constant gear ratio. In addition, pumps are one of heat source in terms of thermal management. The pump work rate also leads to the generation of heat that is then rejected to the fuel stream.

The performance characteristics of these pumps are represented by generic maps stored in AMESim[19]. These maps contain volumetric flow data as a function of pressure difference and rotational speed as shown in Eq. 1.

$$Q = f(\triangle p, N) \tag{1}$$

The fluid temperature rise is computed using the energy balance of Eq. 2.

$$T_{out} = \frac{\dot{W}_{pump}}{\dot{m} c_p} + T_{in} \tag{2}$$

As low pressure and high pressure pumps are installed in the same housing, there can be heat transferred between two components hence, it is interesting to investigate its effect on FTMS.

2.2 Fuel Cooled Oil Cooler

The FCOC(Fuel Cooled Oil Ccooler) is a heat exchanger that extracts heat from the engine oil and heats fuel prior to flow through filter and combustor. The unit is typically a shell and tube type heat exchanger. Fuel pass through the tubes and the oil is guided around the outside of the tubes by baffles in a number of passes. For modeling, the effectiveness and efficiency are implemented using the Eq. 3 and Eq.

4[17]. The efficiency variations for various heat exchangers are represented as a function of capacity ratio[20].

$$\epsilon_{steady} = \frac{|\phi_{steady}|}{|c_{\min}(T_{hot,in} - T_{cold,in})|} \tag{3}$$

$$\epsilon_{th,steady} = \frac{T_{hot,in} - T_{hot,out}}{T_{hot,in} - T_{cold,out}} \tag{4}$$

2.3 Fuel Filter

The purpose of the fuel filter is to protect the downstream units from contaminants. It is equipped with a bypass valve, which operates by a differential pressure due to impending blockage. For modeling, only its pressure drop characteristics are considered.

2.4 Fuel Metering Unit

Fuel metering is controlled by engine controller equal to the demanded flowrate. The modeling of fuel scheduling is accomplished by controlling the orifice area and the fuel pressures at the opposing ends of the metering valve simultaneously. Metering valve maintains a constant pressure difference(Δp) independent of metering valve position.

2.5 Spilled Fuel Flow

Typically high pressure pump delivers excess flow relative to the demand, since the capacity of pump is proportional to engine shaft speed. This surplus fuel is spilled back into the back of low pressure pump in the modeling.

3. Simulation Condition

A typical commercial flight[21] is assumed with further simplification and mission profile from Trent rough values is shown in Fig. 5 and Table 1[22]. The mission profile has seven segments, ground idle, take-off, Climb, cruise, descent, flight idle and ground idle to last 5,460 seconds. The duration time of each mission was adjusted for FTMS model. For an integrated thermal management model including the AVS and PS model, the information of Mach number and altitude is critical, however only fuel flowrate and shaft speed were required for FTMS modeling in the present study. As shown in Table 1, fuel flowrate and the temperatures of fuel and oil are defined as a constant value for each mission segment.

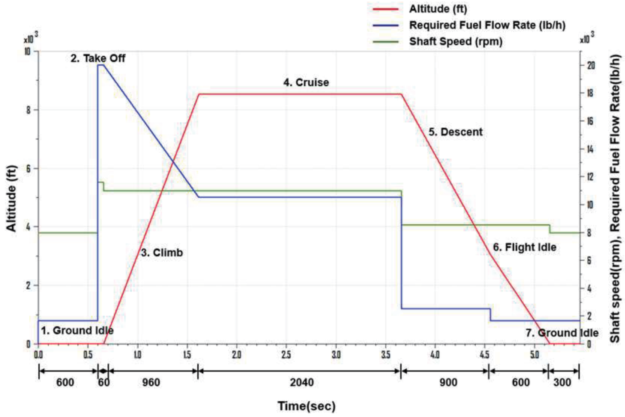

Fig. 5 Mission Profile for Simulation

Table 1 Mission Profile

No	Mission	Altitude (ft)	Duration (sec)	Engine Shaft Speed	Required Fuel Flow Rate (lb/h)	Fuel Inlet Temperature (℃)	Oil Inlet Temperature (℃)
1	Ground Idle	0	600	65%	1,670	33	121
2	Take-off	0	60	95%	20,000	33	170
3	Climb	0 ~ 28,000	960	90%	20,000 ~ 10,500	33	170
4	Cruise	28,000	2,040	90%	10,500	27	150
5	Descent	28,000 ~ 10,000	900	70%	2,500	27	150
6	Flight Idle	10,000 ~ 0	600	70%	1,670	27	150
7	Ground Idle	0	300	65%	1,670	33	150

4. Simulation Results

4.1 Fuel and Oil Temperature through FCOC during Take-off

It is important to characterize the thermal behavior of FCOC as it is a key component of FTMS. To monitor the validity of the current modeling approach, fuel and oil temperatures are simulated at take-off condition only. Figure 6 shows the simulation results for 5 seconds. Actual simulation time was 10 seconds but the temperature shows no variation after 5 seconds. Due to the difference in thermal capacity of two fluids, the temperature variation in the early period of take-off is different.

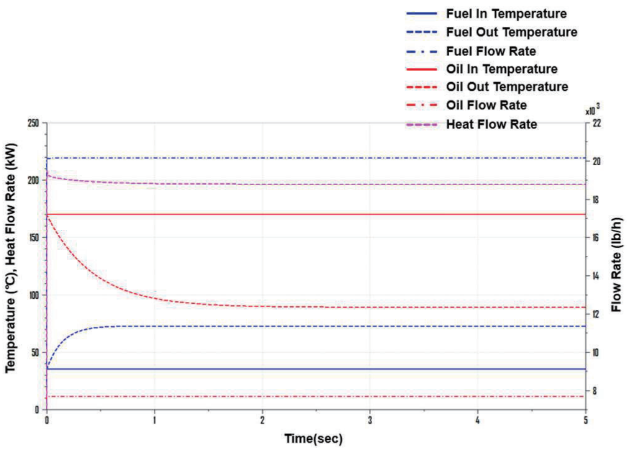

Fig. 6 Thermal Characteristics of FCOC during take-off

The modeling of FCOC is implemented as a part of FTMS model. The temperature behaviors of fuel and oil is simulated for mission profile as shown in Fig. 7.

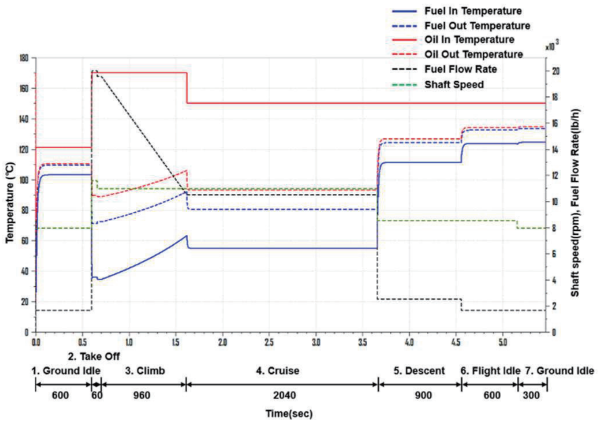

Fig. 7 Temperature Histories of Fuel and Oil at FCOC

Fuel and oil temperatures varies as mission changes in accordance to FCOC characteristic. Fuel temperature steadily increases for climb since its flowrate decreases. Similarly the temperature continues to increase for descent and flight idle while fuel flowrate decreases.

4.2 Temperature History of Fuel through Mission Profile

Figure 8 show the history of fuel temperature at each sub-component during the mission. The increase of fuel temperature is large at FCOC due to the heat exchange with oil flow. Fuel temperature steadily increase for the period of climb with decrease of fuel flow rate in accordance to increasing altitude. The characteristics of temperature variation downstream of FCOC are similar because there is no heat interaction with other systems.

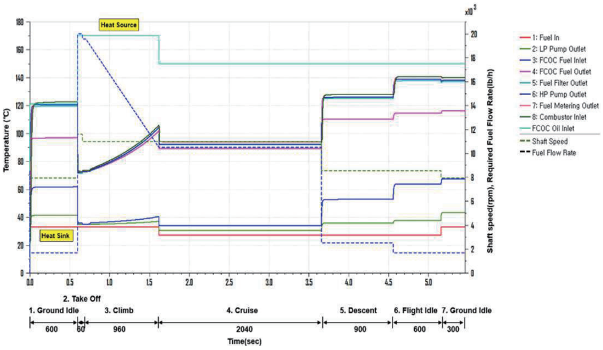

Fig. 8 Fuel Temperature Histories at Each Sub-component

4.3 The Effect of Spilled Flowrate to Fuel Temperature

Returning hot fuel spilled from the fuel metering unit to the FCOC inlet effects on fuel temperature in the combustor inlet. Typically high pressure pump delivers excess flow relative to the demand, because the flow capacity is proportional to engine speed. The spill flow rate is very small for the period of take-off and cruise in contrast to descent, flight idle and ground idle. Figure 9 show the characteristics of fuel temperature in accordance to the spill flow ratio. The spill flowrate depends on pipe diameter ratio(d/D) which is represented as pipe diameters of spill flow(d) and fuel flow(D). In this case, durations were modified for computation time at a level of about 10%. However, the duration of take-off is maintained without modification to monitor characteristic of fuel temperature variation for the rapid increase of fuel flow.

Fuel temperature increases in proportion to increase of spill flow rate for the period of climb and cruise. However, it decreases in reverse proportion to increase of spill flow rate for the period of descent, flight idle and ground idle. It means that the heat transferred to the fuel increases when fuel flow rate is small and results in increase of fuel temperature.

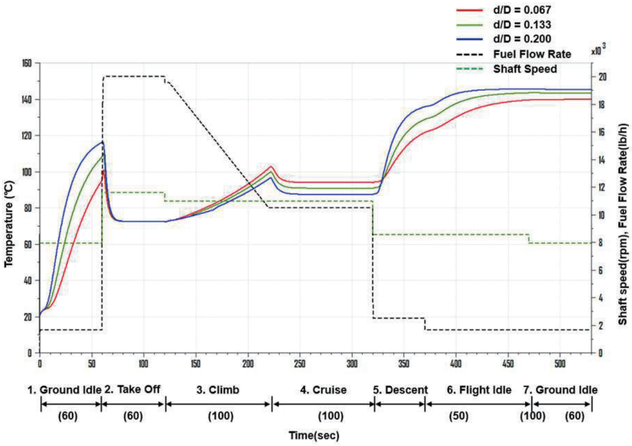

Fig. 9 Characteristics of Fuel Temperature in accordance to Spill Flow

4.4 The Influence of the Thermal Conductivity of LP/HP Fuel Pump Housing

As the low and high pressure pumps are installed in the same housing, it is important to investigate the effect of thermal interaction between two components. Two cases are investigated for the periods of take-off, cruise and descent and only one case employ the thermal interaction with thermal conductivity of 237W/m·K[23]. The material of pump was assumed as pure aluminum in this paper. Table 2 and Fig. 10 show simulation conditions and fuel temperature histories for two cases.

Table 2 Simulation Condition and Result

Mission	Take-off		Cruise		Descent	
Fuel Flow Rate (lb/hr)	20,000		10,500		2,500	
Thermal Conductivity (W/m·K)	0	237*	0	237	0	237
LP Pump Outlet(℃)	33.37	34.72	27.34	29.85	27.20	35.37
HP Pump Outlet(℃)	72.15	71.86	80.90	80.43	124.81	123.97
Combustor Inlet(℃)	72.93	72.64	81.44	80.97	125.12	124.28

* Material: Aluminum, pure

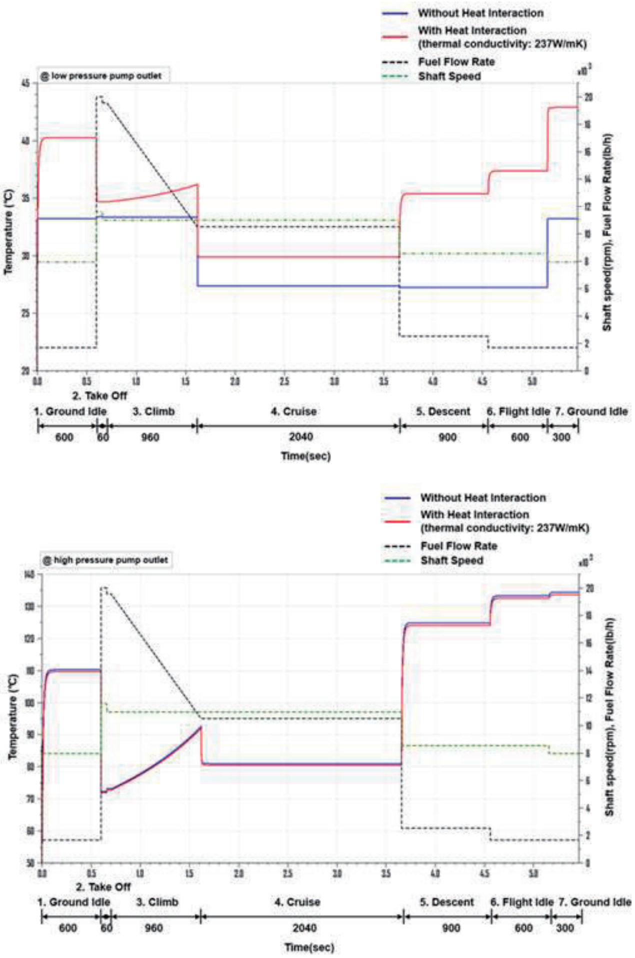

Fig. 10 Temperature Histories at Fuel Pump

Heat load in fuel system strongly depends on fuel flow rate and is significantly increased for the periods of cruise and descent with decrease of fuel flow rate rather than for the periods of take-off. Due to the thermal interaction in pump housing, fuel temperature at the outlet of low pressure pump was increased 4.0%, 9.2% and 30.0% than the case without thermal interaction for take-off, cruise and descent, respectively.

5. CONCLUSION

An architecture of system level thermal management of a typical commercial aircraft is built for modeling and simulation of fuel system, which is a key part of FTMS. The study shows thermal interactions between fuel and engine lubrication oil through the mission profile for a high bypass ratio, two-spool turbofan. Fuel temperature is monitored as it flow through each sub-components of fuel system during the mission. Fuel temperature increases in proportion to increase of spill flow rate for the period of climb and cruise. However, it decreases in reverse proportion to increase of spill flow rate for the period of descent, flight idle and ground idle. It means that the heat which is transferred to the fuel increases when fuel flow rate is small and result in increase of fuel temperature. As the low and high pressure pumps are installed in the same housing, it is important to investigate the effect of thermal interaction between low pressure pump and high pressure pump. Heat load in fuel system strongly depends on fuel flow rate and is significantly increased for the periods of cruise and descent with decrease of fuel flow rate rather than for the periods of take-off. Due to the thermal interaction in pump housing, fuel temperature at the outlet of low pressure pump was increased 4.0%, 9.2% and 30.0% than the case without thermal interaction for take-off, cruise and descent, respectively.

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