A Description of Cyber-Physical Aspects for Thermal Modelling of an Aircraft Fuel System

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The cyber and physical aspects of a fuel system of an aircraft needed for thermal modelling are considered in this paper. This paper is divided into three main sections. The sections entail the physical aspects, the cyber aspects, and the architecture of the cyber-physical model representing the aircraft fuel system.

1. The Physical Aspects of an Aircraft Fuel System

The fuel system hardware representing the main hardware of the system such as the fuel tanks, valves, pumps, and heat exchangers are a physical aspect of the fuel system. This aspect is described in §1.1. Another physical aspect of the fuel system is the environment that the aircraft operates and how it operates. This is typically represented by the mission profile of the aircraft. The mission profile fidelity for a fuel system thermal analysis study is presented in §1.2.

1.1 Fuel System Architecture

The layout of the fuel system hardware is shown in Figure 1. The tank layout is similar to the Gripen aircraft as shown in [1]. The layout in FIGURE 1 consists of four fuselage tanks, namely, T1, T2, T3, and NGT (negative g-acceleration tank). T1 and NGT will be referred to as the engine feed tanks since they directly feed fuel to the engine while all other tanks transfer fuel to these tanks. The NGT is used to ensure fuel supply to the engine during inverted flying (for negative g-acceleration) and therefore fuel cannot be transferred from NGT to T1. T4-R and T4-L represent the wing tanks. The actual tank shapes are not considered in this report such the delta wing tanks or saddle-shaped fuselage tanks that are present in the Gripen aircraft. The tanks are cuboid-shaped tanks however, their volume and fuel mass capacity are similar to the Gripen aircraft. The dimensions and properties of the fuel tanks are shown in Table 1.

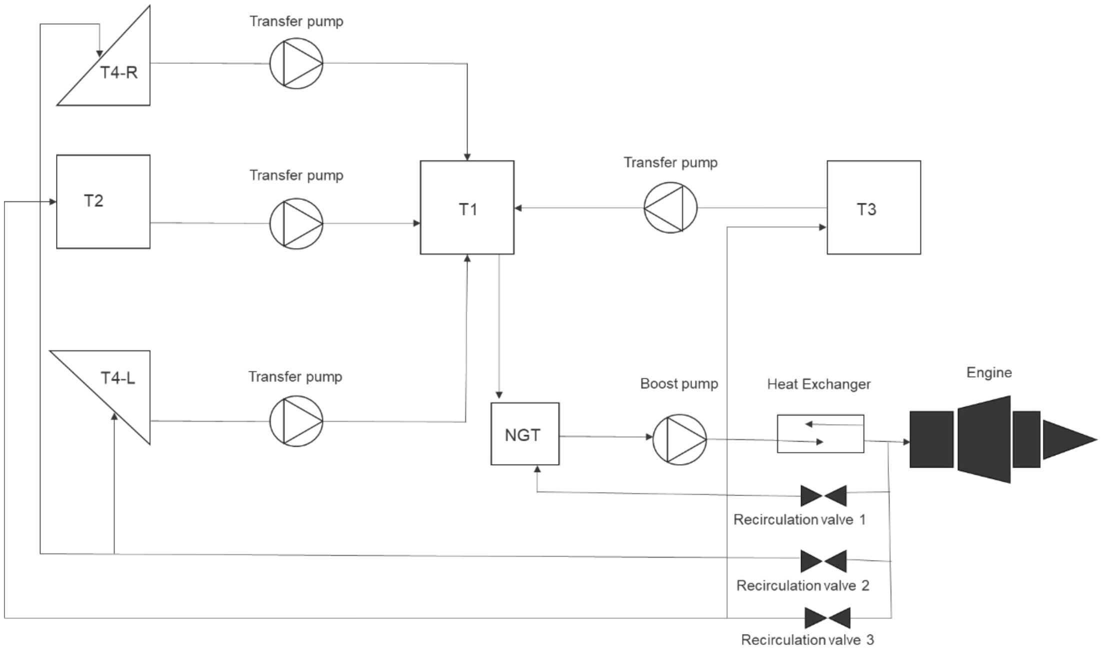

Figure 1 The layout of the aircraft fuel system hardware

Table 1 Parameters of aircraft fuel tanks

Tank	**Fuel mass (kg)**	**Tank Volume (m^3)**	**Total tank surface area exposed to ambient conditions (m^2)**	**Total tank surface area exposed to aircraft internal bay (m^2)**
T1	700	0.95	4	2
T2	500	0.69	3	3
T3	500	0.65	3	3
T4R	500	0.64	4	0
T4L	500	0.64	4	0
NGT	250	0.35	0	0

There are two types of pumps in this system, namely, boost pump and transfer pump. The boost pump delivers fuel to the engine and the transfer pump transfers fuel between the fuel tanks. Simplified characteristic curves for the boost pump and the transfer pump are shown in Figure 2. The fuel system is used to cool a part of the waste heat energy produced by other subsystems of the aircraft. The waste heat energy is transferred to the fuel system via the heat exchanger. The heat exchanger as seen in FIGURE 1 is placed just before the engine so that fuel absorbs that heat before being combusted in the engine. Valves are used to modulate the fuel flow in the system. Finally, there are various types of aviation fuel available as described in [1]. A fuel that is typically used for military jet aircraft is JP-8. The properties of JP-8 can be found in [2].

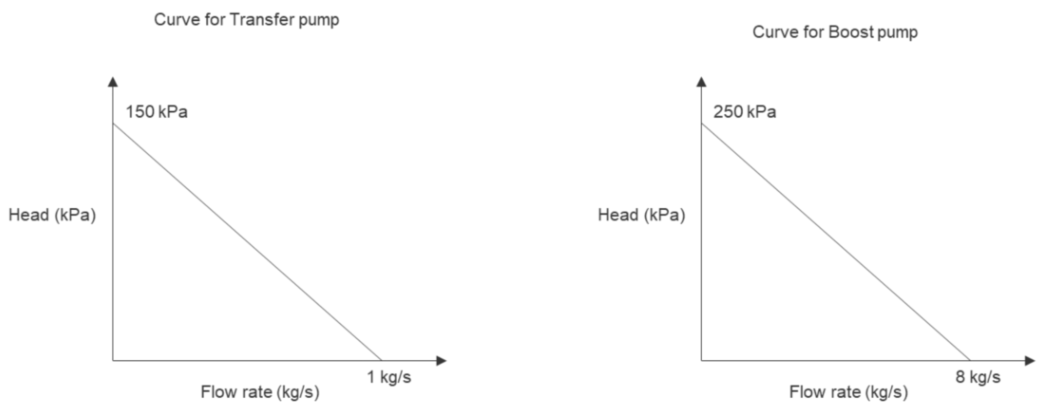

Figure 2 Characteristic Pump curve for transfer pump and boost pump

1.2 The Mission Profile

The parameters of an aircraft mission profile suffice to conduct a thermal analysis of the fuel system are Mach number, fuel consumption rate, heat flow rate (to the fuel system heat exchanger), and altitude. The values of the parameters for various segments of a mission are shown for three missions in Table 2. The temperature of the ambient air is calculated using International Standard Atmosphere +30 (ISA +30).

Table 2 Aircraft mission profiles in terms

	Time [min]	Mach number	Altitude (m)	Fuel consumption (kg/s)	Heat Load, sensors and other systems (kW)
Low Low Low					
Taxiing	15	0	0	0.1	30
Ingress	40	0.6	500	0.47	40
Engagement	10	0.8	500	0.6	50
Egress	40	0.6	500	0.47	40
Taxiing	15	0	0	0.1	30
High Low High					
Taxiing	15	0	0	0.1	30
Ingress	40	0.6	6000	0.47	40
Engagement	10	0.8	500	0.6	50
Egress	40	0.6	6000	0.47	40
Taxiing	15	0	0	0.1	30
High High High					

Taxiing	15	0	0	0.1	30
Ingress	40	0.6	6000	0.5	40
Engagement	10	0.6	6000	0.5	50
Egress	40	0.6	6000	0.5	40
Taxiing	15	0	0	0.1	30

2. The Cyber Aspects of an Aircraft Fuel System

The cyber aspects refer to the control strategy for the valves and pumps for various operational aspects of the aircraft fuel system. One operational aspect is the emptying sequence of the fuel tanks as described in §2.1. Another operational aspect is the recirculation of fuel to tanks during a low thrust phase of the aircraft and this is described in §2.2

2.1 Emptying Sequence of Aircraft Fuel Tanks

On the Gripen aircraft, the wing tanks (T4-R, T4-L) are emptied followed by the fuselage tanks T2 and T3, and finally the engine feed tanks, T1 and NGT. This is shown in Figure 3. An alternate emptying sequence would be emptying fuselage tanks (T2, T3) before the wing tanks as shown as Alternate Sequence 1 in Figure 3. A third sequence would be emptying fuselage tanks (T2, T3) and wing tanks (T4-R, T4-L) simultaneously as shown as Alternate Sequence 2 in Figure 3.

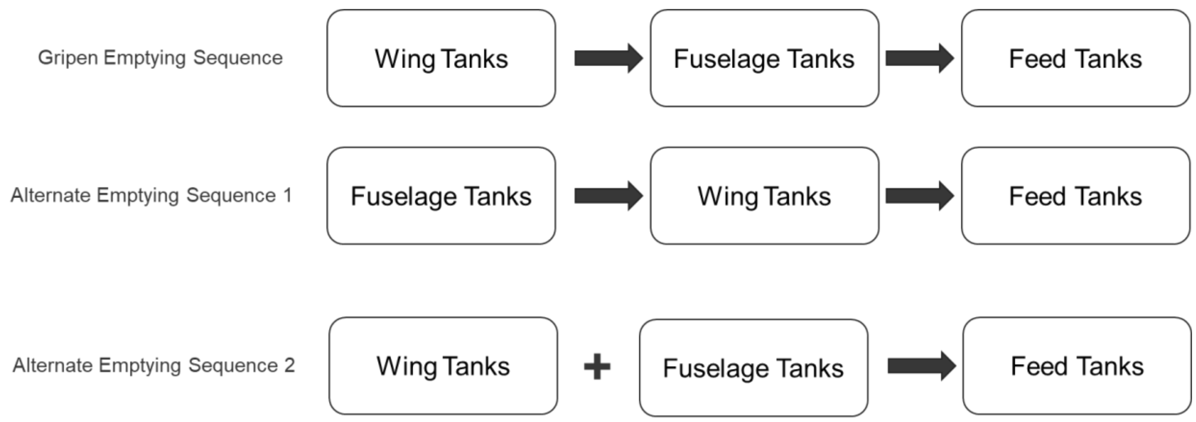

Figure 3 Fuel tank emptying sequences

2.2 Recirculation of Fuel to Tanks

Recirculation of fuel to tanks is useful when the aircraft requires low thrust from the engine. During this low thrust phase, the fuel consumption rate of the engine is low. Therefore, for the fuel system architecture at hand in Figure 1, the fuel mass flow rate through the heat exchanger would also be low. For the heat exchanger to be able to cool the same heat flow rate it is required to, then according to equation [1], the fuel mass flow rate is the only parameter that can be increased.

$$\dot{Q_{Hx}} = \dot{m_{fuel}}\, c_p (T_{outlet_{Hx}} - T_{inlet\ Hx}) \qquad \text{equation [1]}$$

$\dot{Q_{Hx}}$ – heat flow rate in kW that the heat exchanger of the aircraft fuel system is required to cool

$\dot{m_{fuel}}$ – mass flow rate of the fuel in kg/s through the heat exchanger

c_p – specific heat capacity of fuel (kJ/(kg °C))

$T_{outlet_{Hx}}$ - outlet temperature of the fuel from the heat exchanger in °C

$T_{inlet\ Hx}$ - inlet temperature of the fuel from the heat exchanger in °C

The inlet temperature of the fuel, $T_{inlet\ Hx}$ to the heat exchanger is set by the NGT. The outlet temperature of the fuel from the heat exchanger, $T_{outlet_{Hx}}$ is set by the inlet threshold temperature of the fuel to the engine (in this case it is assumed to 80°C). Therefore, the fuel is recirculated to the tanks to increase the fuel mass flow rate through the heat exchanger. The recirculation strategy can entail recirculating to either the wing tanks (T4-R, T4-L) or fuselage tanks (T2, T3). At any point in a mission being simulated, this would be based on which set of tanks has the smaller amount heat flow rate into the tanks and if that set of tanks were not already full (this would be based on the fuel tank emptying sequence employed). When fuel recirculation is needed and if the wing tanks are not full and had a smaller amount heat flow rate into them compared to the fuselage tanks, then 'Recirculation valve 2' in Figure 1 would be opened, while recirculation valves 1 and 3 would stay closed.

3. The Cyber-Physical Architecture of an Aircraft Fuel System

The cyber-physical architecture of the aircraft fuel system is shown in Figure 4. This architecture can be modelled in system modelling tools such as Modelon Impact, Dymola, or Matlab Simulink or a combination of the tools.

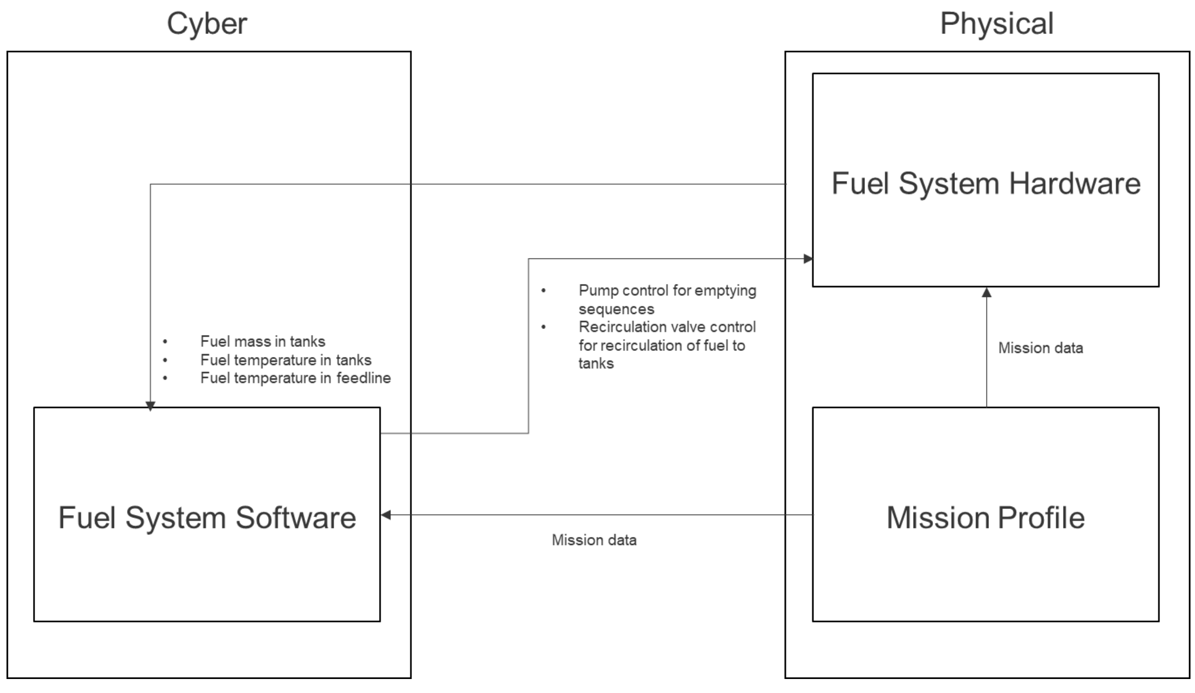

Figure 4 The cyber-physical architecture of an aircraft fuel system

4. References

[1] H. Gavel, "On Aircraft Fuel Systems Conceptual Design and Modeling," Linköping University, Linköping, 2007.

[2] Coordinating Research Council, "Handbook of Aviation Fuel Properties," Society of Automotive Engineers, 1983.