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MANAGEMENT AND CONTROL OF A FLEXIBLE AIRCRAFT FUEL THERMAL SYSTEM

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ABSTRACT

An optimal dynamic method (OPT) is proposed to validate the FLEX algorithm proposed earlier by the authors. FLEX is a robust control strategy which provides an adaptable configuration framework for increasing the thermal endurance of aircraft that use fuel as a heat sink for internal waste thermal energy. FLEX algorithm was implemented to switch between four different modes of operation during a flight mission to achieve the goal of extending thermal endurance. OPT, which is optimized to control the maximum fuel temperature and at the same time to reduce the waste energy storage in the system, has been found to follow exactly the same path for configuration mode changes as proposed by the FLEX algorithm. This seems to indicate that the current thermal management and control strategy may be optimal.

1. INTRODUCTION

The generation of waste thermal energy within modern aircraft has increased with advances in avionics and weaponry systems. Fuel is used as a heatsink and a medium by which waste thermal energy is removed from an aircraft. The method by which fuel flow is managed can have a significant impact on aircraft thermal endurance.

Figure 1 shows two fuel thermal systems presented by Doman [1-4]: single and dual tank configurations. In Fig. 1, m and T are the mass and temperature of fuel in the tank and the subscripts 1 and 2 indicate the tank locations; $\dot{Q}_h$ is the heat load; $\dot{Q}_c$ is the heat transfer rate for a ram air cooler and can be expressed as [1-4]:

$$\dot{Q}_c = \left(\dot{m}_f - \dot{m}_e\right) c_p \left(T_h - T_w\right)\left\{1 - \exp\left[-UA / \left(c_p (\dot{m}_f - \dot{m}_e)\right)\right]\right\}; \tag{1}$$

where $\dot{m}_f$ and $\dot{m}_e$ are the mass flow rates of the feeding and exiting flows, respectively; U is overall heat transfer coefficient; A is the contact surface area; T_w is the constant wall temperature of heat exchanger; T_h and T_c are the fuel temperatures at the exits of the heater and cooler, respectively.

Fuel flow in excess of engine demands may be required for cooling and this excess fuel passes through a ram air cooler prior to returning to the single storage tank. The single tank configuration, Fig 1(a), is intrinsically unsteady as the system is constantly losing fuel to the engine. The temperature of the storage tank, T_1, can continue to rise and the accumulation of excessive energy may cause T_h to exceed its limit, which in the present application is $r_{T_h} = 421K$. It should be noted that T_h is the hottest point of the system and therefore it is where the temperature limit is applied. The time it takes for the fuel temperature to reach its limit is called the thermal endurance. The design goal is not only to develop a fuel thermal system to prolong the thermal endurance such that it is equal to the fuel duration limit but also to maintain the fuel temperature after the heater to be as close to the fuel temperature limit as possible in order to provide a more efficient combustion of the fuel in the engine and to maximize the

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disposal rate of waste thermal energy throughout the flight mission. Doman has demonstrated that a dual tank system can prolong thermal endurance [1]. However, Doman's original dual tank design was not intended to accommodate for a surge of heat load during a flight mission, which may cause T_h to exceed the limit even when the mass flow rate of the feedline runs at its maximum limit, $\dot{m}_f = \overline{\dot{m}_f} = 3.5\,kg/s$. To remedy this problem, Huang et al. [5, 6] proposed a FLEX topology to improve upon Doman's dual tank design and a new algorithm has been developed to enable control strategies to be executed in a segregated manner. The algorithm was formulated based on an enumerative carpet search of the solution contour [5, 6]. The purpose of the current work is to use a dynamic optimization approach to show that the algorithm presented by Huang et al. was indeed the optimal one and a unique solution can be identified using this algorithm.

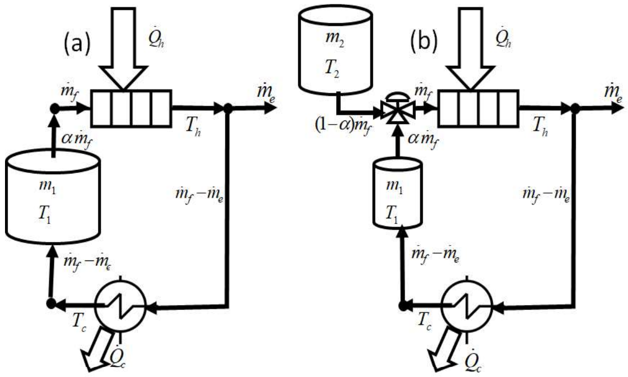

Figure 1 Single and dual tank fuel thermal management system.

In Section 2, the FLEX topology and an algorithm for the management of an aircraft fuel thermal system will be reviewed. In Sections 3, a dynamic optimization approach (OPT) is presented to manage and control the aircraft fuel thermal system. The solution will be presented in Section 4. It will be shown that OPT produces the same solution path as that proposed by the FLEX algorithm and the solution for the mission is identical that presented earlier. This implies that the optimal solution may be optimal. Finally, conclusions are presented in Section 5.

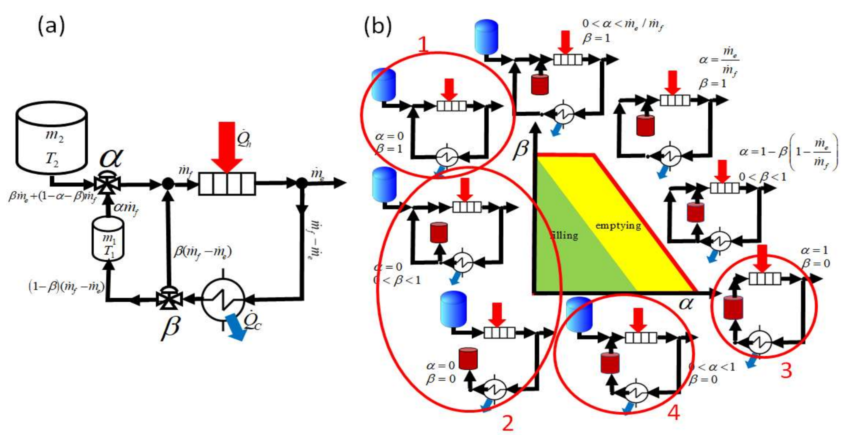

Figure 2 FLEX fuel thermal system (Huang et al. [5, 6]).

2. FLEX TOPOLOGY

The FLEX system proposed by Huang et al. is shown in Fig. 2 (a) [5, 6], in which T_h and T_c can be derived from an energy balance and are given by:

$$T_h = \frac{\dfrac{\dot{Q}_h + \left(1-\eta\dfrac{\dot{m}_f}{\overline{\dot{m}_f}}\right)P_P}{\dot{m}_f c_p} + \alpha T_1 + \left[\beta\dfrac{\dot{m}_e}{\dot{m}_f} + (1-\alpha-\beta)\right]T_2 + \beta\left(1-\dfrac{\dot{m}_e}{\dot{m}_f}\right)\left[1-\exp\left(\dfrac{-UA}{c_p(\dot{m}_f-\dot{m}_e)}\right)\right]T_w}{1-\beta\left(1-\dfrac{\dot{m}_e}{\dot{m}_f}\right)\exp\left(\dfrac{-UA}{c_p(\dot{m}_f-\dot{m}_e)}\right)}, \quad (2)$$

and
$$T_c = T_h - \frac{\dot{Q}_c}{c_p(\dot{m}_f - \dot{m}_e)}, \quad (3)$$

where P_P is pump power and η is the efficiency of the pump.

The topology is controlled by the adjustment of α and β valves to achieve many different flow configurations, as shown in Fig. 2(b). α and β are continuously variable between 0 and 1. The fuel in the feedline can be a mixture of up to three streams which originate from a reservoir tank (tank 2), recirculation tank (tank 1) and bypass. The respective mass flow rates from these elements are given by: $\beta\dot{m}_e + (1-\alpha-\beta)\dot{m}_f$, $\alpha\dot{m}_f$, and $\beta(\dot{m}_f - \dot{m}_e)$. The returning fuel from the ram air cooler is split by the β valve into two streams: one directly to the feedline and the other to the recirculation tank for storage. Although many configurations are possible with the FLEX topology, a combination of only four configurations as circled in red in Fig. 2(b) were recommended in the algorithm of Huang et al. [5, 6] to maximize thermal endurance. These configurations are called: 1. steady-state, 2. filling, 3. self-emptying and 4. assisted-emptying processes. The flowchart for the FLEX algorithm is illustrated in Fig. 3.

When tank 1 is empty ($m_1 = 0$), the steady-state process is attempted by setting $\alpha = 0$ and $\beta = 1$. The solution for $\dot{m}_f$ will be sought to satisfy $T_h = r_{T_h}$. If a solution is not found or if it returns a mass flow rate value larger than the limit, $\overline{\dot{m}_f}$, the filling stage will be activated by allowing the recirculation tank to temporarily store a portion of hot fuel.

The main feature of FLEX is its ability to store excessive hot fuel in the recirculation tank (tank 1) when the system is subject to large heat load transients that would otherwise cause the thermal equilibrium temperature to rise above the temperature limit, r_{T_h}. In the filling stage, the valve from the recirculation tank to the feedline is shut ($\alpha = 0$) and the flow rate runs at its maximum value, $\dot{m}_f = \overline{\dot{m}_f}$. An adjustment is made to the bypass ratio of the returning fuel to the feedline, β, such that $T_h = r_{T_h}$.

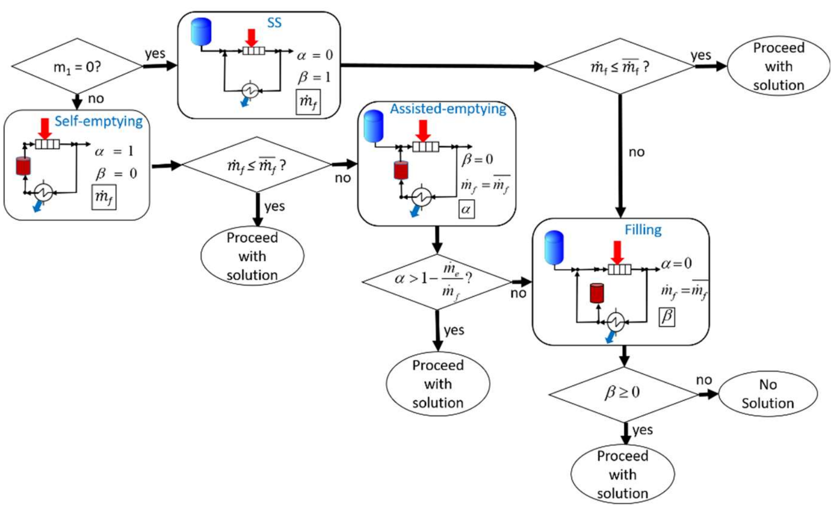

Figure 3. FLEX Algorithm (Huang et al. [5, 6].

Within the FLEX algorithm, when m_1 not equal to 0, emptying processes are checked for feasibility prior to selecting the filling process. This precedence of operations ensures that the accumulation of waste thermal energy onboard the aircraft is minimized. The self-emptying process tested enables the mass flow rate of the feedline, $\dot{m}_f$, to be solely supplied by the recirculation tank ($\alpha = 1$ and $\beta = 0$) to enable $T_h = r_{T_h}$. This process will enable the fastest disposal rate of the accumulated energy in the system. However, the fuel in tank 1 may be so hot that the fuel temperature at the heater output exceeds a limit even when the fuel runs at its maximum flow rate, $\dot{m}_f = \overline{\dot{m}_f}$. In this case, the mass flow rate of the feedline will maintain its maximum value while adjustment of α is made to mix the hot flow from tank 1 with cold fuel from tank 2. This is called the assisted-emptying process. The criterion for the assisted-emptying process is that the resulting α value must lead to more flow rate exiting the storage tank than entering, or $\alpha \dot{m}_f > \dot{m}_f - \dot{m}_e$. If this condition is not satisfied, the filling stage is activated.

3. OPTIMAL DYNAMIC SOLUTION (OPT)

The optimal solution can be obtained by minimizing the cost function, *J:*

$$J = \min_{\dot{m}_f,\alpha,\beta} \int_o^{t_f} \left[A\left(T_h - r_{T_h}\right)^2 + B\left(1-\alpha\right)^2 + C\left(1-\beta\right)^2 \right] dt \tag{4}$$

subject to

$$\frac{dm_1}{dt} = \left(1-\beta\right)\left(\dot{m}_f - \dot{m}_e\right) - \alpha \dot{m}_f, \tag{5}$$

$$\frac{dT_1}{dt} = \frac{\left(1-\beta\right)\left(\dot{m}_f - \dot{m}_e\right)\left(T_c - T_1\right)}{m_1}, \tag{6}$$

$$\frac{dm_2}{dt} = -\beta \dot{m}_e - \left(1-\alpha-\beta\right)\dot{m}_f, \tag{7}$$

$$\dot{m}_e \le \dot{m}_f \le \dot{m}_{f,\max},\ 0 \le \alpha \le 1 - \beta\left(1 - \frac{\dot{m}_e}{\dot{m}_f}\right) \text{ and } 0 \le \beta \le 1, \tag{8}$$

where the value of *A* is set to 100 while the values of *B* and *C* are set to 1. The requirement to set α and β as close to 1 as possible is to ensure the energy accumulation in the system can be minimized. The choice of a larger value of coefficient *A* is to put more weighting on satisfying $T_h = r_{T_h}$.

The cost function, Eq. 4, is solved subject to the constraints given in Eqs. 5-8. The solution procedure is similar to the one described in Huang and Doman [3]. The inverse design requires the determination of control trajectories that optimize the performance measure defined by minimizing the cost function, *J*, along the path from $t = 0$ to $t = t_f$, where t_f is total operation time elapsed. To do this, the differential equations are discretized into algebraic forms using a first order implicit finite difference approximation. The associated Lagrangian then yields:

$$\nabla H = \nabla J + \lambda_1 \left| \frac{m_1 - m_1^n}{\Delta t} - \dot{m}_1 \right| + \lambda_2 \left| \frac{T_1 - T_1^n}{\Delta t} - \dot{T}_1 \right| = 0 \tag{9}$$

where λ_1 and λ_2 are Lagrange multipliers; the superscript *n* denotes the value at the previous time step; $\dot{m}_1$ and $\dot{T}_1$ are given in the RHS of Eqs. 5 and 6, respectively.

Equation 9 consists of seven equations: $\partial H / \partial m_1 = 0$, $\partial H / \partial T_1 = 0$, $\partial H / \partial \dot{m}_f = 0$, $\partial H / \partial \alpha = 0$, $\partial H / \partial \beta = 0$, $\partial H / \partial \lambda_1 = 0$ and $\partial H / \partial \lambda_2 = 0$. These coupled nonlinear algebraic equations are solved implicitly using the Newton Raphson method. If the solution is within the constrains listed in Eq. 8, an optimized solution is achieved for time *t*. On the other hand, if the solution is not available or the solution does not satisfy the state constraints in Eq. 8, then the optimal solution will be located at the boundary of the state constraints. A combination of different possibilities leads to a total of 18 additional scenarios consisting of cases subject to having one or two constraints. There are 6 possibilities in the single-constraint cases - the upper and lower limits of $\dot{m}_f$, α and β, and 12 possibilities in two-constraint cases - the combinations of the upper and lower limits of ($\dot{m}_f$, α), ($\dot{m}_f$, β), and (α, β). The number of equations to be solved is reduced from 7 to 6 and 5, when the number of constraints increases from 0 to 1 and 2, respectively. The equations to be eliminated are those associated with the constrained variables. The solution is determined by the successive reduction of order (from 7 to 5 equations) and whichever gives the lowest value of *J* is the optimal solution at time *t*. In the next section it will be shown that the current method gives the same solution as that found using enumeration search [5, 6], which is simply a brute force search of an optimized solution to ensure $T_h = r_{T_h}$.

4. SIMULATION OF A FLIGHT MISSION

This test case is proposed by Huang et al. [5, 6] and the operating conditions for different mission phases are given in Table 1. The thermal heat load, $\dot{Q}_h$ and the heat generated by the pump due to pump inefficiency, $\dot{Q}_P = \left(1-\eta\dot{m}_f / \overline{\dot{m}_f}\right)P_P$, have created a large combined heat load, $\dot{Q}_H = \dot{Q}_h + \dot{Q}_P$. When using only the steady-state process, this large heat load causes the fuel temperature to exceed its limit during the engagement period (between 3000 and 7000 seconds). With the FLEX configuration, dynamic optimization approach selects the filling process to overcome this difficulty as shown in Fig. 4(a) and after the engagement period, the self-emptying process is used to discharge the hot fuel in the storage tank. This path is exactly what the FLEX algorithm suggested. The solution by OPT is identical to those reported by Huang et al. [5] and this demonstrates the FLEX algorithm offers an optimal path for thermal management.

As can be observed in Figs. 4 (a) and (e), the mass in tank 1 is accumulated at a rate of 6% of the returning flow rate ($\beta = 0.94$) during the engagement period (3000-7000 seconds). The remaining 94% of the returning hot fuel converts to 83% of the feedline mass flow rate while 17% of feedline fuel is from tank 2. Comparisons of T_h and T_c for the FLEX and steady-state topologies are given in Fig.4(b). The temperature obtained with the steady-state topology exceeds the limit during the engagement period because the mass flow rate has reached its upper bound and hot returning fuel cannot be stored in the steady-state case, as shown in Fig. 4(c). In contrast, the FLEX system maintains bounded temperature behavior throughout the entire mission. In particular, T_h is constant at 421 K except during the aircraft climb region (in the vicinity of 1800 seconds) where $\dot{m}_f = \dot{m}_e$ and the value of $\dot{m}_e$ is higher than the desired mass flow rate that is necessary to maintain $T_h = r_{T_h}$. The filling process continues until the end of the engagement period (7000 seconds). After that, the aircraft undergoes a series of operations including egress cruise, descent, landing and ground hold, in which the heat load has dropped

Table 1 Operating conditions of a notional flight mission (Huang et al. [5, 6]).

time (sec)	$\dot{m}_e$ (kg/s)	$\dot{Q}_h$ (kW)	T_w (K)	η	P_P (kW)
0	0.088	28	288	0.3	40
1799	0.088	28	288	0.3	40
1800	3.5	51	288	0.5	70
1927	1.93	51	238	0.5	70
1928	0.26	61	238	0.45	50
3000	0.26	61	238	0.45	50
3001	0.4	211	238	0.5	70
7000	0.4	211	238	0.5	70
7001	0.29	66	238	0.45	50
9009	0.29	66	238	0.45	50
9010	0.26	51	238	0.375	50
9332	0.26	51	288	0.375	50
9333	0.088	28	288	0.3	40
14850	0.088	28	288	0.3	40

significantly. Hence, the fuel from tank 1 alone is sufficient to maintain $T_h = r_{T_h}$. As can be seen during the emptying stage, between 7,000 and 10,000 seconds, the mass of tank 2 stays constant and the mass of tank 1 drops almost linearly. It should be noted that the mass flow rate of the feedline (100% contributed by tank 1) continues to drop, as shown in Fig. 4(c), because the temperature of tank 1 continue to decrease due to lowering of the temperature of the returning fuel at the exit of the ram air cooler. Finally, after approximately $10,000$ sec, the FLEX topology switches to the steady-state mode. The current solution is identical to that obtained by the FLEX algorithm given in [5, 6].

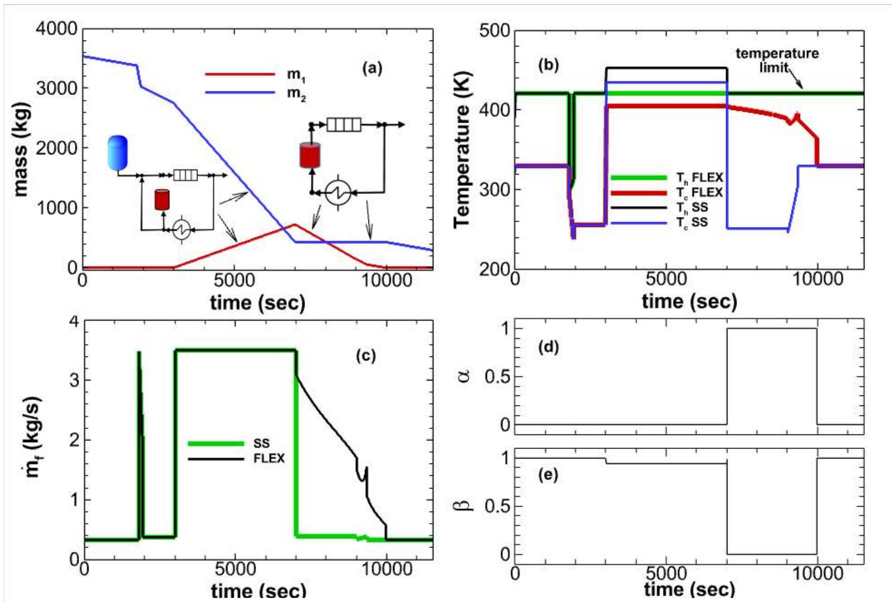

Figure 4 Solution of OPT under a flight mission with extended high-heat-load engagement zone.

5. CONCLUSIONS

The current paper used a dynamic optimization approach to determine the optimal flow path and control input settings within the FLEX topology and it was found that the solution matches exactly that obtained using the FLEX algorithm. It demonstrated that the FLEX algorithm can produce an optimal path for the FLEX fuel thermal management system and the same solution can be achieved by the dynamic optimization method.

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