Heat Transfer Calculation of Civil Aircraft Fuel Tanks Considering Combined Heat Transfer Effects

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Abstract. To improve the safety and thermal management efficiency of civil aircraft fuel tanks, this study investigates key components of wing-mounted tanks - specifically the tank skin and fuel pump - by developing a thermal model that accounts for combined heat transfer mechanisms. A semi-analytical explicit solution method, based on the heat balance integral method, is proposed to derive the heat transfer expressions. The accuracy of the derived results is validated through theoretical analysis. Considering the combined effects of convection, radiation, and combined convection and radiation on both the tank skin and the fuel pump, the overall heat transfer and temperature distribution within the fuel are further derived based on the principle of energy conservation. The proposed methodology and results demonstrate strong engineering relevance and offer promising potential for broader application in aircraft thermal design.

Keywords: Amount of heat transfer; combined heat transfer; unsteady state heat transfer; fuel tank; civil aircraft.

1. Introduction

Effective thermal management of civil aircraft fuel systems is critical to ensuring flight safety. As composite materials become increasingly prevalent in modern aircraft structures, conventional thermal analysis methods - primarily based on lumped parameter models are proving inadequate for addressing complex boundary conditions and internal heat sources. The coexistence of multiple heat transfer mechanisms within fuel tanks presents additional challenges, highlighting the need for efficient and accurate methods to compute transient heat transfer. Such approaches are essential for enhancing the precision and reliability of thermal assessments in fuel system design.

The temperature within aircraft fuel tanks can be analyzed using mathematical methods. Guo et al. [1] derived a quantitative relationship between equilibrium temperature difference and thermal time constant, and proposed a method for calculating the thermal parameters of fuel tanks. Zhang [2] conducted an engineering analysis of a representative fuel tank under typical hot-day conditions (ambient temperature of 327 K), identifying temperature variation trends, the timing of peak temperatures, and their spatial locations, thereby providing technical support for tank design. Doman et al. [3,4] developed differential equations to describe fuel temperature variations within the frameworks of fuel-temperature-constrained mission planning, trajectory optimization, and analytical thermal management scheduling. These methods demonstrated high efficiency while simplifying the planning of aircraft thermal management systems. Furthermore, a methodology was introduced to evaluate the impact of fuel flow topology and control strategies on thermal endurance. Mathematical models were established to characterize fuel flow and temperature behavior in both single- and dual-tank configurations. The results showed that a closed-loop dual-tank system offers significantly improved thermal endurance compared to open- or closed-loop single-tank systems. Oppenheimer et al. [5] proposed a mathematical model for aircraft thermal management, considering the influence of fuel pump size on thermal durability. Additionally, a control strategy was developed to maintain fuel temperature within safe operational limits.

This study centers on two critical heat transfer components within the fuel system: the wing skin and the fuel pump. Building upon previously established heat conduction models and the heat balance integral method [6], analytical expressions for heat transfer are derived under composite heat transfer conditions, encompassing convection, radiation, and combined convection and radiation scenarios. Drawing on the heat transfer mechanisms of the wing fuel tank and the principle of energy conservation, predictive formulas describing the temporal evolution of fuel heat transfer and temperature are subsequently developed.

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2. Heat Transfer Modeling and Methodology

For the wing fuel tank, both the wing skin and the fuel pump can be modeled as one-dimensional heat conduction problems. Based on references [7,8], the following assumptions are made:
(1) the wing is modeled as a semi-infinite flat plate with finite thickness, and the fuel pump is idealized as a cylindrical body;
(2) heat conduction is one-dimensional, with temperature varying only in the thickness direction of the skin and the radial direction of the cylinder;
(3) the wing skin and the fuel pump are assumed to be opaque to thermal radiation;
(4) the surrounding fluid medium of both the wing skin and the fuel pump does not impede thermal radiation;
(5) the thermal properties of the wing skin and the fuel pump are temperature-independent and treated as constants;
(6) the heat transfer coefficients of the wing skin and the fuel pump are independent of the outer surface temperature;
(7) there are no internal heat sources or sinks in the wing skin; the fuel pump contains a uniformly distributed internal heat source, and its central axis is adiabatic.
To analyze the external and internal heat transfer of the wing fuel tank, mathematical models are developed with clearly defined assumptions, initial conditions, and boundary conditions. The heat balance integral method is then applied to perform the calculations. The detailed procedure of this method is as follows:
(1) Establish the governing heat conduction equation based on the defined assumptions, initial conditions, and boundary conditions;
(2) Integrate the heat conduction equation to convert it into a heat balance integral form;
(3) Propose an approximate temperature distribution function, typically expressed as a polynomial [9,10];
(4) Substitute the assumed temperature profile into the integral equation to derive the time-dependent parameters of the temperature distribution.
The approximate temperature distribution function, together with the resulting ordinary differential form of the governing equation, is further employed to explicitly solve for the boundary temperature and temperature gradient.

3. Heat Transfer Calculation of Wing Fuel Tank Skin

The heat flux q at the outer surface of the wing skin depends on the external surface temperature; thus, the heat transfer can be represented in a normalized form as:

$$\frac{Q}{Q_s}=\int\frac{qd\tau_1}{\rho_1 Lc_1\left(T_m-T_i\right)} \tag{1}$$

In the equation, Qs denotes the maximum theoretical heat transfer through the skin, expressed as Qs=c1m1(Tm-Ti) , where ρ1 is the density of the skin material, L is the skin thickness, c1 is the specific heat capacity of the skin material, Tm is the ambient temperature outside the fuel tank, and Ti is the initial temperature of the skin. The heat transfer process is divided into two stages: the heat penetration stage, represented by Q1, and the post-penetration stage, represented by Q2. By substituting the ordinary differential form of the governing equation for the skin into Eq. 1, the expressions for Q1 and Q2 are derived respectively.
Stage 1: heat penetration in the skin (0⩽δ1<δτ1)

$$\frac{Q_1}{Q_s}=\frac{q\delta_{\tau1}^2}{6\lambda_1 L\left(T_m-T_i\right)} \tag{2}$$

In the equation, δτ1 represents the thermal penetration depth, and λ1 is the thermal conductivity of the wing.
Stage 2: post-penetration phase of the skin (δ1=δτ1)

$$\frac{Q_2}{Q_s}=\left.\frac{3\lambda_1 T_a L-qL^2}{3\lambda_1 L\left(T_m-T_i\right)}\right|_{Fo_{p1}}^{Fo_1} \tag{3}$$

In the equation, Ta denotes the temperature on the outer surface of the skin, and Fo1 is the Fourier number corresponding to the skin's thermal penetration time. The normalized heat transfer expressions for the two stages will be applied to calculate the heat transfer under the three thermal conditions of the wing skin.

3.1 Heat Transfer Under Convection

By integrating the temperature distribution under convection with Eq. 2, the heat transfer during the thermal penetration stage can be formulated as follows:

$$\frac{Q_1}{Q_s}=\frac{B_{i1}\delta_1^2}{6+3B_{i1}\delta_1}\quad Fo_1\le Fo_{p1} \tag{4}$$

In the equation, Bi1 denotes the Biot number of the skin, defined as Bi1=(L/λ1)/(1/h1), and δ1 is the normalized thermal penetration depth, given by δ1=δτ1/L. By combining the temperature distribution under convection conditions with Eq. 3, the heat transfer during the post-penetration stage under convection can be derived as follows:

$$\frac{Q_2}{Q_s}=\frac{6+2B_{i1}}{6+3B_{i1}}-\frac{6+2B_{i1}}{6+3B_{i1}}\exp\left[-\frac{3B_{i1}}{3+B_{i1}}\left(Fo_1-Fo_{p1}\right)\right]\quad Fo_1>Fo_{p1} \tag{5}$$

By summing the results from Eqs. 4 and 5, the total heat transfer for the convection case can be determined.

$$\frac{Q}{Q_s}=1-\left(\frac{6+2B_{i1}}{6+3B_{i1}}\right)\exp\left[-\frac{3B_{i1}}{3+B_{i1}}\left(Fo_1-Fo_{p1}\right)\right] \tag{6}$$

3.2 Heat Transfer Under Radiation

By combining the temperature distribution under radiation with Eq. 2, the heat transfer during the thermal penetration stage under radiation can be derived as follows:

$$\frac{Q_1}{Q_s}=\frac{2\left(t_a-t_i\right)^2}{3B_{i1}^r\left(1-t_i\right)\left(1-t_a^4\right)} \quad Fo_1\leq Fo_{p1} \qquad (7)$$

In the equation, t represents the dimensionless temperature, defined as $t=T/T_m$, and $B_i{}^r{}_1$ is the radiation Biot number of the skin, given by $B_i{}^r{}_1=T_m{}^3L\varepsilon_1\sigma/\lambda_1$. By combining the temperature distribution under radiation with Eq. 3, the heat transfer during the post-penetration stage under radiation can be derived as follows:

$$\frac{Q_2}{Q_s}=\frac{t_a\left(3+B_{i1}^r t_a^3\right)-t_a^p\left[1+B_{i1}^r\left(t_a^p\right)^3\right]}{3\left(1-t_i\right)} \quad Fo_1>Fo_{p1} \qquad (8)$$

By summing Eqs. 7 and 8, the total heat transfer during the radiation process can be obtained.

$$\frac{Q}{Q_s}=\frac{t_a-t_i}{1-t_i}-\frac{B_{i1}^r}{3}\frac{1-t_a^4}{1-t_i} \qquad (9)$$

3.3 Heat Transfer Under Combined Convection and Radiation

By combining the temperature distribution under combined convection and radiation with Eq. 2, the heat transfer during the thermal penetration stage under combined effects can be derived as follows:

$$\frac{Q_1}{Q_s}=\frac{2\left(t_a-t_i\right)^2}{3\left(1-t_i\right)\Omega_a} \quad Fo_1\leq Fo_{p1} \qquad (10)$$

In the equation, Ωa represents the dimensionless heat flux density at the outer surface of the skin, defined as $\Omega_a=qL/T_a\lambda_1$. By combining the temperature distribution under combined convection and radiation with Eq. 3, the heat transfer during the post-penetration stage under radiation can be derived as follows:

$$\frac{Q_2}{Q_s}=\frac{3t_a-t_a^p-2t_i-\Omega_a}{3\left(1-t_i\right)} \quad Fo_1>Fo_{p1} \qquad (11)$$

By summing Eqs. 10 and 11, the total heat transfer during the combined convection and radiation process can be obtained.

$$\frac{Q}{Q_s}=\frac{3t_a-3t_i-\Omega_a}{3\left(1-t_i\right)} \qquad (12)$$

As the duration of each of the three thermal loads becomes sufficiently long, the heat transfer process reaches a steady state, with the normalized heat transfer quantities converging to 1. This confirms the accuracy of Eqs. 6, 9, and 12.

4. Heat Transfer Calculation of Wing Fuel Pump

The external heat flux qs on the surface of the fuel pump depends on the wall temperature and is influenced by an internal heat source $\dot{q}$. Therefore, the heat transfer can be expressed in a dimensionless form as follows:

$$\frac{Q}{Q_p}=\int\frac{\dot{q}+q_s}{\rho_2 c_2 R\left(T_\infty-T_0\right)}d\tau_2 \qquad (13)$$

where Qp represents the maximum theoretical heat transfer of the fuel pump, defined as $Qp=c2m2(T\infty-T0)$, ρ2 is the density of the pump material, R is the pump radius, c2 is the specific heat capacity of the pump material, T∞ is the temperature of the surrounding medium, and T0 is the initial temperature of the pump. The heat transfer process consists of two stages: the heat penetration stage, denoted as Q1, and the post-penetration stage, denoted as Q2. By substituting the ordinary differential form of the control equation for the fuel pump into Eq. 13, the following result is obtained:

Stage 1: heat penetration in the pump (0⩽δ2<δτ2)

$$\frac{Q_1}{Q_p}=\frac{q_s\delta_{\tau 2}^2\left(4R-\delta_{\tau 2}\right)}{24\lambda_2 R^2\left(T_\infty-T_0\right)} \qquad (14)$$

where δτ2 is the thermal penetration depth, and λ2 is the thermal conductivity of the wing.

Stage 2: post-penetration phase of the pump (δ2=δτ2)

$$\frac{Q_2}{Q_p}=\left.\frac{4\lambda_2 T_s-q_s R}{8\lambda_2\left(T_\infty-T_0\right)}\right|_{Fo_{p2}}^{Fo_2} \qquad (15)$$

where Ts is the outer surface temperature of the skin, and Fo2 is the Fourier number for the fuel pump, representing the thermal penetration time. The normalized heat transfer expressions for the two stages above will be applied to calculate the heat transfer under three working conditions of the fuel pump.

4.1 Heat Transfer Under Convection

By combining the temperature distribution of the fuel pump under convection with Eq. 14, the heat transfer during the heat penetration stage under convection can be derived as follows:

$$\frac{Q_1}{Q_p}=\frac{B_{i2}\delta_2^2\left(4-\delta_2\right)}{24+12B_{i2}\delta_2} \quad Fo_2\leq Fo_{p2} \qquad (16)$$

where Bi2 is the Biot number of the fuel pump, defined as Bi2=(R/λ2)/(1/h2), and δ2 is the normalized thermal penetration depth, defined as δ2=δτ2/R. By combining the temperature distribution of the fuel pump under convection with Eq. 15, the heat transfer during the post-penetration stage under convection can be derived as follows:

$$\frac{Q_2}{Q_p}=\frac{4+B_{i2}}{8+4B_{i2}}-\frac{4+B_{i2}}{8+4B_{i2}}\exp\left[-\frac{8B_{i2}}{4+B_{i2}}\left(Fo_2-Fo_{p2}\right)\right] \quad Fo_2>Fo_{p2} \qquad (17)$$

By summing Eqs. 16 and 17, the total heat transfer under convection can be determined.

$$\frac{Q}{Q_p}=\frac{1}{2}-\frac{4+B_{i2}}{8+4B_{i2}}\exp\left[-\frac{8B_{i2}}{4+B_{i2}}\left(Fo_2-Fo_{p2}\right)\right] \qquad (18)$$

4.2 Heat Transfer Under Radiation

Based on the temperature distribution of the fuel pump under radiation and Eq. 14, the heat transfer during the thermal penetration stage can be derived as follows:

$$\frac{Q_1}{Q_p}=\frac{B_{i2}^r\left(1-t_s^4\right)}{24\left(1-t_0\right)}\left(4\delta_2^2-\delta_2^3\right)\quad Fo_2\le Fo_{p2} \tag{19}$$

Here, t represents the dimensionless temperature t=T/Ts, and Bir2 is the radiation Biot number for the fuel pump, defined as Bir2=T∞3Rε2σ/λ2. Based on the temperature distribution of the fuel pump under radiation and Eq. 15, the heat transfer during the post-penetration stage can be derived accordingly.

$$\frac{Q_2}{Q_p}=\frac{1}{2}\frac{t_s-t_s^p}{1-t_0}-\frac{B_{i2}^r}{8}\frac{\left(t_s^p\right)^4-t_s^4}{1-t_0}\quad Fo_2>Fo_{p2} \tag{20}$$

By summing Eqs. 19 and 20, the total heat transfer during the radiation-dominant process can be determined.

$$\frac{Q}{Q_p}=\frac{B_{i2}^r\left(2\beta t_0^4+t_s^4-2\beta-1\right)+4\left(t_s-t_0\right)}{8\left(1-t_0\right)} \tag{21}$$

In the above equation, β denotes the internal heat source intensity (β= $\dot{q}$ /q0).

4.3 Heat Transfer Under Combined Convection and Radiation

Based on the temperature distribution of the fuel pump under combined convection and radiation and Eq. 14, the heat transfer during the thermal penetration phase can be expressed as follows:

$$\frac{Q_1}{Q_p}=\frac{\Omega_s}{24\left(1-t_0\right)}\delta_2^2\left(4-\delta_2\right)\quad Fo_2\le Fo_{p2} \tag{22}$$

Here, Ωs represents the dimensionless heat flux density at the outer surface of the fuel pump, defined as Ωs=qsR/(Ts λ2). Based on the temperature distribution of the fuel pump under combined convection–radiation conditions and Eq. 15, the heat transfer during the post-penetration phase can be derived accordingly.

$$\frac{Q_2}{Q_p}=\frac{4\left(t_s-t_s^p\right)+\Omega_s^p-\Omega_s}{8\left(1-t_0\right)}\quad Fo_2>Fo_{p2} \tag{23}$$

By summing Eqs. 22 and 23, the total heat transfer during the combined convection and radiation process can be determined.

$$\frac{Q}{Q_p}=\frac{4\left(t_s-t_0\right)-2\beta\Omega_0-\Omega_s}{8\left(1-t_0\right)} \tag{24}$$

As the duration of each of the three thermal loads becomes sufficiently long, the heat transfer process reaches a steady state, with the normalized heat transfer quantities converging to 1/2. This confirms the accuracy of Eqs. 18, 21, and 24.

5. Heat Transfer Calculation of Wing Fuel Tank

According to the heat transfer mechanism of the wing fuel tank, the heat absorbed by the fuel primarily originates from four sources: solar radiation, radiation from the ground or cloud, combined convection and radiation heat transfer through the upper and lower wing skins, and combined convection and radiation heat transfer from the fuel pump with internal heat generation.
Heat transfer from solar radiation E_1

$$Q_{sun}=E_1\left(\frac{t_a-t_i}{1-t_i}-\frac{B_{i1}^r}{3}\frac{1-t_a^4}{1-t_i}\right) \tag{25}$$

Heat transfer from ground or cloud radiation E_2

$$Q_{ground/cloud}=E_2\left(\frac{t_a-t_i}{1-t_i}-\frac{B_{i1}^r}{3}\frac{1-t_a^4}{1-t_i}\right) \tag{26}$$

Heat transfer from combined convection and radiation on upper and lower wing skins

$$Q_{skin}=2\rho_1c_1L\left(T_m-T_i\right)\frac{3t_a-3t_i-\Omega_a}{3\left(1-t_i\right)} \tag{27}$$

Heat transfer from the fuel pump with internal heat generation under combined convection and radiation

$$Q_{pump}=\rho_2c_2R\left(T_\infty-T_0\right)\frac{4\left(t_s-t_0\right)-2\beta\Omega_0-\Omega_s}{8\left(1-t_0\right)} \tag{28}$$

According to the law of energy conservation, the sum of the above four heat transfer components is equal to the total heat received by the fuel, denoted as Q_{fuel}. By substituting Eqs. 25, 26, 27, and 28 into this relationship, we obtain:

$$Q_{fuel}=\left(E_1+E_2\right)\frac{3t_a-3t_i-B_{i1}^r\left(1-t_a^4\right)}{3\left(1-t_i\right)}+2\rho_1c_1L\left(T_m-T_i\right)\frac{3t_a-3t_i-\Omega_a}{3\left(1-t_i\right)}+\rho_2c_2R\left(T_\infty-T_0\right)\frac{4\left(t_s-t_0\right)-2\beta\Omega_0-\Omega_s}{8\left(1-t_0\right)} \tag{29}$$

The fuel temperature T_{fuel} can be expressed as:

$$T_{fuel}=T_0+\frac{\left(E_1+E_2\right)}{c_fm_f}\frac{3t_a-3t_i-B_{i1}^r\left(1-t_a^4\right)}{3\left(1-t_i\right)}+2\frac{\rho_1c_1L\left(T_m-T_i\right)}{c_fm_f}\frac{3t_a-3t_i-\Omega_a}{3\left(1-t_i\right)}+\frac{\rho_2c_2R\left(T_\infty-T_0\right)}{c_fm_f}\frac{4\left(t_s-t_0\right)-2\beta\Omega_0-\Omega_s}{8\left(1-t_0\right)} \tag{30}$$

6. Summary

This study employs a semi-analytical method based on the heat balance integral approach to derive expressions for the heat transfer of the wing fuel tank skin and fuel pump under various operating conditions. Based on the heat transfer mechanisms of the wing fuel tank and the law of energy conservation, the heat transfer to the fuel and its corresponding temperature expression are also derived. The main conclusions are as follows:
(1) The heat transfer of the skin under convection is primarily influenced by the Biot number and penetration Fourier number. Under radiation, the heat transfer depends on the radiation Biot number and the external surface temperature of the skin. For combined

convection–radiation, the heat transfer is determined by both the external surface temperature and the heat flux density.

(2) The heat transfer of the fuel pump under convection is governed by the Biot number and penetration Fourier number. Under radiation, it depends on the radiation Biot number, the external surface temperature of the pump, and the internal heat source intensity. In the combined convection–radiation case, heat transfer is related to the external surface temperature, heat flux density, and internal heat source intensity.

(3) The fuel heat transfer increases with the physical parameters of the skin and fuel pump. The fuel temperature is positively correlated with the physical parameters of the skin and fuel pump, and negatively correlated with the physical properties of the fuel itself.

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