Influence of solar panel on wing aerodynamic characteristics of HALE UAV

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Abstract. HALE UAV needs solar energy to maintain its flight in the day and night. The solar panel located on the upper surface may potentially affect aerodynamic characteristics of the HALE wing. The solar panel generates a heat resulted from solar radiation absorption and surface roughness which becomes parameters to be studied. To identify the phenomena of interaction of flow motion and the heat as well as the roughness, dimensionless numbers such as Reynolds Number (Re), Nusselt Number (Nu), and geometry reference (Ks/C) are used. The simulations for flows at the numbers are conducted using CFD method based on the solution of RANS equations. As a result, the heat transfer gives significant change in flow density near the surface which causes buoyancy effect and the change of flow velocity profile, while the roughness influences the flow characteristics disturbing the flow to become turbulent. They increase aerodynamic drag of 2.6 % and aerodynamic efficiency in the amount of 5%.

Keywords: HALE UAV, solar cell, heating, roughness, aerodynamic characteristics, computational fluid dynamics

1. Background

Most HALE (High Altitude Long Endurance) Unmanned Aerial Vehicles have been developed with various missions such as surveillance, monitoring, mapping, or pseudo-satellite UAV. To fulfill the mission, HALE UAVs have optimal flight conditions at high altitudes, around 60,000 ft above sea level, with long duration flight, more than one day as mentioned by Dalamagkidis [1-2]. Under these flight conditions the UAV needs a lot of energy which are fulfilled by installing solar panels on its wings. The HALE flight operating speed is low around 25 m/s (20 KEAS). Figure 1 shows Solar panels mounted on the upper wing surface of HALE UAV which change airflow around the wing, in turn, influence on aerodynamic performance of the HALE UAV.

There are several factors that the solar panel potentially affect the aerodynamic performance of the HALE UAV namely heat transfer and surface roughness of the solar panel. In addition, the HALE with a long wingspan and low airspeed at high altitude generates low Reynolds number flow over the wing. This may cause airflow in the HALE wing to be easily disturbed, Winslow [3], and the characteristics of low Reynolds numbers flow have a high tendency to occur separations due to external interference.
Solar panel may absorb the radiation exposure from a sunlight emitted from the sun to produce electricity. Then, this absorption emit heat on the surface and interacts with air flow through the solar surface changes aerodynamic characteristics of the HALE UAV wing. Research conducted by Kumar [5] and Samiee [6] explains that the heat transfer that occurs on an airfoil affected the aerodynamic performance of the airfoil.

In addition, the solar panel surfaces have roughness that may alter laminar air flow to become turbulent. This causes the frictional forces that occur on the surface increases. This problem is closely related to airflow at a low Reynolds number where the location of the transition point occur earlier. Experiments carried out by Chakroun [7] prove that roughness on the wing surface will affect its aerodynamic performance, especially the addition of a large drag.

2. Basic Theory

2.1 Low Reynolds Number Flight

Air flow at low Reynolds numbers has special characters which dominate by viscous effect on flow field near the surface. This viscosity produces a friction affecting aerodynamic performance of a body. There is a condition called no-slip condition where flow velocity at the surface is equal to zero and the velocity change gradually in a normal direction with respect to the surface and meets uniform velocity at outer region. A boundary region where a dominant viscosity effect inside is called as the boundary layer as sketched for the boundary layer on an airfoil in Figure 2. The boundary layer also has several regions which are divided based on flow characteristics. The region having regular flow streamlines and calm properties are called laminar occurred in the starting of the boundary layer, while the region with irregular and convoluted air streamlines are called turbulent. Both of flow regions have different forms of velocity profiles. In a fluid flow, these two flow regions may occur simultaneously. The connection between them is a transition region.

Alsahlani [2] states that there are several factors to be considered in the aerodynamic design of the HALE UAV. The operations of the HALE at very high altitude with low velocity flight may occur at a small Reynolds number which may produce a great impact on aerodynamic design of the HALE UAV. At that altitude, the atmosphere density is low, to keep the flight position at a given speed the UAV should be designed to have airfoil with high lift coefficient at low Reynolds number. In addition, airfoil characteristics at low Reynolds numbers are strongly influenced by laminar flow separation. [3]
There are several factors of flow transition including velocity and turbulence of freestream flow, adverse pressure gradient, roughness and heat transfer. These factors may give alteration of fluid properties inside the boundary layer such as density, temperature and viscosity. Fluid density and viscosity can be changed due to temperature, as governed by the ideal gas law in Equation 1, and Sutherland’s law in Equation 2. [8]

\[
p = \rho RT
\]

\[
\mu = \left( \frac{T}{T_0} \right)^\frac{3}{2} \left( \frac{T_0 + 110}{T + 110} \right)
\]

The frictional force on the airfoil surface depend on viscosity and fluid velocity gradients in the boundary layer in the normal direction of the surface as written in Equation 3. [8]

\[
\tau_{wall} = \mu(T) \left( \frac{\partial n^i}{\partial n} \right)_{wall}
\]

The fluid properties in the flow field around an airfoil may be obtained by solving Navier-Stokes equations which consists of continuity equation, momentum equations and energy equation as given in Equations 4 to 6, respectively [8].

\[
\nabla \cdot \mathbf{V} = 0
\]

\[
\rho \frac{\partial \mathbf{V}}{\partial t} + \rho (\mathbf{V} \cdot \nabla) \mathbf{V} = -\nabla p + \rho \mathbf{g} + \nabla \cdot \mathbf{\tau}
\]

\[
\rho \frac{\partial n^i}{\partial t} + \nabla \cdot (p\mathbf{V}) = \rho \mathbf{q}_{rad} + \nabla \cdot \mathbf{\dot{q}} + \nabla \cdot (\mathbf{V} \cdot \mathbf{\tau}) + \nabla \cdot (\mathbf{\lambda} \nabla T)
\]

Where \( \mathbf{V}, \rho, p, T, \mathbf{\tau}, \mathbf{g}, h_t, \mathbf{\dot{q}} \) are velocity, density, pressure, temperature, shear stress, gravity, total enthalpy and heat transfer rate, respectively.

### 2.2 Computational Fluid Dynamics Simulation

The simulations are conducted by Computational Fluid Dynamics method solving the governing equations on spatial discrete points in a computational domain. The computation uses a computer to do iterative numerical process of the discrete equation either in explicit direct solution or implicit matrix solution. The boundary conditions are required in the simulation to obtain more realistic solution. The boundary conditions may be applied on body surface, incoming and outcoming flows as well as farfield boundary. In addition, the solution of flowfield can be extracted from values of fluid properties at every nodal in the computational domain. Figure 3 shows the steps that used for CFD simulation. [9]
Figure 3. CFD Simulation Flowchart

The boundary layer on the CFD can be captured by adjusting the minimum meshing height on the airfoil surface. The height needs to be adjusted to the $y^+$ approach which is closely related to $u^+$. Equations 7 to 9 set the values of $u^+$ and $y^+$. Small $y^+$ (below 5) is needed to capture the boundary layer. [10]

$$ u^+ = \frac{u}{u_*} $$

$$ y^+ = \frac{\rho u_* y}{\mu} $$

$$ u_* = \frac{\tau_{wall}}{\sqrt{\rho}} $$

(7)  
(8)  
(9)

The shear stress and friction coefficient uses the Equations 10 and 11 respectively, [11].

$$ \tau_{wall} = C_f \frac{1}{2} \rho U^2 $$

$$ C_f = (2(Re_x) - 0.65)^{-2.3} $$

(10)  
(11)

The study is conducted by using ANSYS Fluent software to model the heat transfer on the wing surface. The heat flux or the wall temperature is required as an input for boundary conditions of the system. The roughness is modelled by sand-grain parameter uses conservation values. The values of the roughness for this study are given in Table 1. [12]

| Roughness Parameter | $R_a$ | $R_{RMS}$ | $R_{zd}$ |
|---------------------|-------|-----------|----------|
| Estimated Sand-Grain Roughness, $\varepsilon$ | $\varepsilon = 5.863$ | $\varepsilon = 3.100$ | $\varepsilon = 0.978$ |

Table 1. Surface Roughness Conversion Parameter Value.

2.3 HALE UAV Design

The specification of the wing design of the HALE UAV is used to be analyzed are listed in Table 2. The airfoil on HALE UAVs uses K3311 airfoil. This airfoil has the shape as shown in Figure 4.

Figure 4. K3311 Airfoil
Table 2. Analyzed Aircraft Design’s Dimension.

| Parameter                  | Value | Unit |
|----------------------------|-------|------|
| MTOW                       | 50.00 | Kg   |
| Chord                      | 0.85  | M    |
| Wing Span                  | 15.00 | M    |
| Wing Area                  | 12.75 | m²   |
| Taper Ratio                | 1.00  | -    |
| Cruise Speed (target)      | 25.00 | m/s  |
| Cruise Altitude (target)   | 18.00 | Km   |
| Cruise Altitude (target)   | 60.00 | Kft  |

3. Modelling

The analysis is conducted for cruise conditions with variation of parameters adjusted for the altitude of the flight. The cruise conditions are on altitude 60,000 ft with angle of attack of two degrees. The air properties used for the analysis are shown in Table 3. The variation parameters are the heat flux (W/m²) and sand-grain roughness (K_s/c). The extreme values of the parameters, used to show the design point, is the maximum heat absorption according to Wasfi [13] and roughness of the solar cell [14].

Table 3. Air Properties on Altitude 60,000 ft

| Altitude  (ft) | Pressure (Pa) | Density (kg/m³) | Temperature (K) | Reynolds Number |
|----------------|---------------|-----------------|-----------------|----------------|
| 60,000         | 7171.64       | 0.115318        | 216.65          | 15 x 10⁴        |

Figures 4 and 5 show the wing mesh formed with a C-type topology of multi-block consisting of subdomains for the wing with the computational domain size of 5 times of the wing chord for radius of the freestream inlet and 15 times of wing chord for the downstream. The mesh density and shape are adjusted according to the needs of the flow physics. Around the surface of the wing, the finer mesh is made to capture the viscous flow on the airfoil.

Figure 5. Mesh for HALE UAV Wing
Table 4. Properties for Boundary Conditions on the Mesh.

| Parameter | Value                      | Unit                                                                 |
|-----------|----------------------------|----------------------------------------------------------------------|
| Inlet     | Velocity                   | front, top, bottom, and right wing farfield                          |
| Solar Panel | Wall                     | upper wing surface at 0.1-0.9 chord                                  |
| Skin      | Wall                       | the entire wing surface is outside the definition                     |
| Symmetry  | Symmetry                   | surface on the wing root                                             |
| Outlet    | Pressure                   | farfield the back of the wing                                        |

4. Simulation Results and Analysis

The validation is done by comparing the simulation results of K3311 airfoil with experiments taken from the reference book "Summary of Low-Speed Airfoil Data" by Michael S. Selig [15]. Figures 6 and 7 show lift and drag coefficients of HALE wing at zero angle of attack at various Reynolds numbers. From this comparison data, the simulation yields small value of error below than 5%. It explains that the simulation can capture effect of low Reynolds Number well.

![Figure 6](image1.png)  
(a) Figure 6. Comparison of simulation and experiment for wing with Airfoil K3311: (a) lift coefficient and (b) drag coefficient

![Figure 7](image2.png)  
(b) Figure 7. Comparison of simulation and experiment for wing with Airfoil K3311: aerodynamic efficiency

Figure 8 and 9 shows the effect of the combination of heat flux and roughness on drag and aerodynamic efficiency, respectively. The values of design point at heat flux of 1000 W/m² is also provided in the graphs.
The simulation results for off-design condition are performed at lower and higher heat flux and higher sand grain size. The decrease in drag can be obtained by reducing heat flux at lower sand-grain size less than 0.02 %. While, for higher heat flux above 1000 W/m², the drag increases and becomes linearly higher increases with larger sand-grain size. In addition, aerodynamic efficiency of the HALE UAV wing becomes higher with reducing heat flux at lower sand-grain size less than 0.02 %. But the reduction of aerodynamic efficiency occurs when the heat flux increases. This reduction in efficiency will result in an increase in the power needed by the HALE UAV.

Figure 8. $C_D$ Graph UAV HALE Wings and Extreme Design Points

Figure 9. L/D Graph UAV HALE Wings and Extreme Design Points

Figure 10 depicts the effect of heating and roughness on friction and turbulence intensity. The effect of heat flux of the solar panel gives slightly increase in local friction coefficient and turbulent intensity in the position of 10-90% of the wing chord. While, the effect of roughness gives higher increases in local friction coefficient and turbulent intensity in the position of 10-90% of the wing chord. The transition region moves forward due to the roughness.
These simulations conclude that the effects of heat flux and roughness due to the installation of solar panels on aerodynamic characteristics of the HALE UAV is quite significant. The drag of the HALE wing increases by 2.6% and the decreased aerodynamic efficiency by 5.1% on the extreme possibility. With these results, we can be sure that the HALE UAV wing is quite safe from the influence of solar panels installed on the surface of the wing.

This extreme point is likely to occur during the day, where the sun is shining with the maximum heat at very high altitudes. Based on the previous analysis, the highest possible heat flux that occurs when this condition can reach 1000 W/m². In fact, the heat flux varies depending on the altitude of flight, latitude and longitude, season, and time (morning, afternoon, or evening). By analyzing the extreme condition, the possibilities of the effect of the flux and roughness on aerodynamic characteristics of the HALE wing can be ascertained to be smaller.

5. Conclusion

Based on the simulation results, it can be concluded that the installation of the solar panel as HALE wing surface gives quite significant influence the HALE UAV aerodynamic performance due to heat transfer and surface roughness. The decrease in drag can be obtained by reducing heat flux at lower sand-grain size less than 0.02 %. For higher heat flux above 1000 W/m², the drag becomes linearly higher increases with larger sand-grain size. Aerodynamic efficiency of the HALE UAV wing increases with reducing heat flux at lower sand-grain size less than 0.02 %, vise versa. The effect of heat flux of the solar panel gives slightly increase in local friction coefficient and turbulent intensity in the position of 10-90% of the wing chord. While, the roughness affects higher increases in local friction coefficient and turbulent intensity in the position of 10-90% of the wing chord. In extreme conditions, where the HALE UAV is operating on its main mission...
during the day, the influence has quite significant effect on the flow characteristics caused the change of aerodynamics performance in less than 5%.

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