Improvement of Aerodynamic Performance of Oscillating Airfoils with Plunging Motion at Low Reynolds Numbers Using Heat Transfer

A. Samiee[1], M. H. Djavareshkian[2], M. Honarmand[3]

1-Introduction

Due to importance of Micro Aerial Vehicles (MAV), many studies have been done to develop this field of research. Motivation of recent attempts is to improve aerodynamic performances in Low Reynolds Number (LRN) flow. Therefore, many methods including optimization of airfoil shape, blowing and suction are used in these researches to modify these performances. On the other hand, theory of using heat transfer based on viscous boundary layer characteristics can also be utilized to improve the aerodynamic efficiencies. The main objective of this paper is to investigate effects of heat transfer on aerodynamic performance of symmetric and non-symmetric airfoils with plunging motion. Hence, the fluid flow is assumed viscous, compressible and unsteady with Re of 20000. Navier-Stokes equations are discretized by Finite Volume Method (FVM) and are solved by PIMPLE algorithm. Also the influence of heat transfer on vortices pattern of trailing edge and consequently on aerodynamic performance of airfoil is analyzed. Results indicated that cooling surface of NACA4412 airfoil can increase the mean lift to drag ratio up to 87.8% than the condition without heat transfer while heating decreases this ratio to 91%. Also in low reduced frequency, vortices pattern is being in drag generation style at all conditions of heat transfer. However, by increase in reduced frequency, vortices pattern will be changing in order to produce thrust in cooling condition.

2- Numerical Method

Flow properties are not generally constant with temperature alteration. With assumption of an isobar state changing, air density decreases by temperature enhancement while dynamic viscosity and thermal conductivity increase. Moreover, specific heat remains stable and Prandtl number decreases slightly. Evaluation of air physical properties indicates that these properties are changed inherently and should be exerted in computation. Thermal conductivity is obtained by Eucken relation. Dynamic viscosity is evaluated by Sutherland model.

Conservation laws of mass, momentum and energy are governing equations. Derivations of these equations are mentioned by different references. For current research, flow field around airfoil is solved by equations of continuity, compressible Navier-Stokes and energy which are shown as bellow, respectively:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_{\mathrm{i}}}(\rho u_{\mathrm{i}}) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_{\mathrm{i}}) + \frac{\partial}{\partial x_{\mathrm{j}}}(\rho u_j u_{\mathrm{i}}) = \frac{\partial \tau_{\mathrm{ij}}}{\partial x_j} - \frac{\partial p}{\partial x_{\mathrm{i}}} \tag{2}$$

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_{\mathrm{j}}}(\rho u_{\mathrm{j}} h) = \frac{\partial}{\partial x_{\mathrm{j}}}\left(\frac{k_T}{C_p}\frac{\partial h}{\partial x_{\mathrm{j}}}\right) + \frac{Dp}{Dt} \tag{3}$$

where $i = 1, 2$ are x and y coordinates, respectively. u_i indicates velocity through i direction. Enthalpy is expressed by $h = e + {}^{p}/_{\rho}$. ${}^{Dp}/_{Dt}$ shows substantial derivative of pressure and computes accomplished work by pressure. Converted kinematic energy to heat by viscous loss is small in comparison with other terms and can be neglected. Flow is assumed Newtonian and fully laminar. Governing equations in vector condition and independent of coordinates can be shown as bellow:

$$\frac{\partial}{\partial t}(\rho\varphi) + \nabla.\left(\rho\varphi(U - U_{\mathrm{g}})\right) = \nabla.(\Gamma\nabla\varphi) + S_{\varphi} \tag{4}$$

where φ is variable and can be u, v and h and U_g is mesh velocity. In other words, dynamic mesh is used for changeable geometry. Equation 4 is discretized by FVM and is solved by pressure based algorithm. In the current study, diffusion and convection terms are discretized by second order central and upwind difference, respectively. Also fully implicit method of Euler is used to discretize temporal terms. Temporal integration on diffusion and convection terms can be accomplished by explicit or implicit method. However, due to stability condition, implicit scheme is better than explicit one. In this research, discretized equations are solved by PIMPLE algorithm. As known, this algorithm is combination of SIMPLE and PISO algorithms. SIMPLE algorithm is applied by PIMPLE one as a new outer loop in the PISO algorithm

3- Results and Discussion

Schematic of plunging motion is shown in Fig. 1. C-type mesh is used to model the flow around the airfoil in this paper. General scheme of C-type mesh is shown in Fig. 2. In order to validate performed simulations, results of present research are compared with those of Hinz, Alighanbari. Drag coefficient of present simulations are compared with those of mentioned research in Fig. 3. This figure shows high accuracy of present simulation in comparison with numerical data of Hinz, Alighanbari. At first, influence of heat transfer in cooling and heating

---

[1] M.Sc., Ferdowsi University of Mashhad.
[2] Corresponding Author: Associate Professor, Ferdowsi University of Mashhad. javareshkian@um.ac.ir
[3] M.Sc., Ferdowsi University of Mashhad.

conditions is investigated on a NACA0012 airfoil with plunging motion. Surface temperatures of 200, 250, 300, 350 and 400 k are considered. Due to legibility, instantaneous lift coefficient for only surface temperatures of 200, 300 and 400 k is demonstrated in Fig. 4. According to this figure, cooling increases maximum instantaneous lift coefficient slightly while heating decreases this coefficient. As shown in Table 1, by enhancement of temperature to 400 k, maximum lift coefficient reduces almost 7.5%. However, this coefficient is increased about 3.8% by reduction of temperature to 200 k. It should be noted that due to symmetric geometry of airfoil, mean lift coefficient is zero in all conditions. Based on Fig. 4, sinusoidal form of lift coefficient diagram is slightly changed by cooling and heating. Instantaneous drag coefficient is shown in Fig. 5.

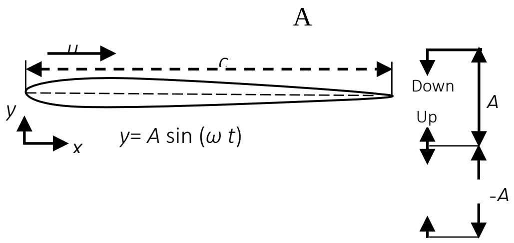

Fig. 1 schematic of plunging motion.

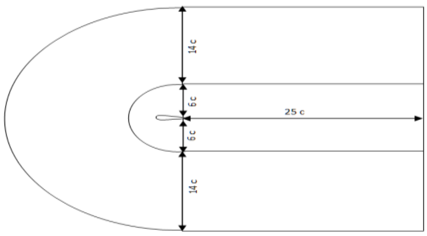

Fig. 2 C-type mesh around airfoil.

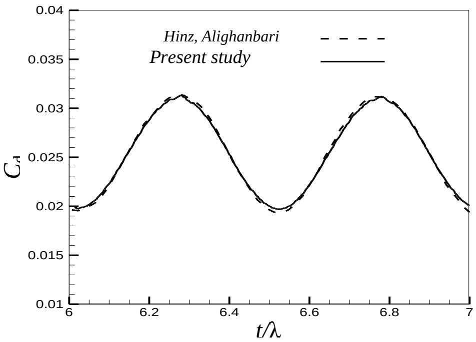

Fig. 3 Validation for drag coefficient of NACA0012 airfoil, $\boldsymbol{Re = 20000, K = 3.93, H = 0.0125, T_\infty = 300\ K, T_S = 350\ K}$.

Table1 Maximum lift coefficient for various surface temperatures of NACA0012 airfoil

	$T_s = 200K$	T_s=250K	T_s=300K	T_s=350K	T_s=400K
$C_{l,max}$	1.1286	1.1106	1.0875	1.0569	1.0115

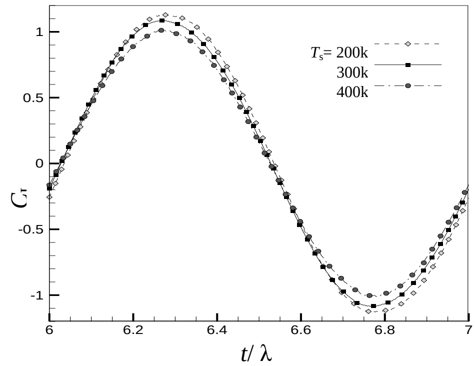

Fig. 4 Lift coefficient for various surface temperature of NACA0012 airfoil, Re = 20000, K = 3.93, H = 0.0125.

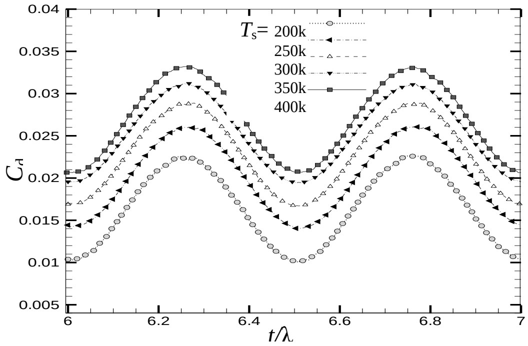

Fig. 5 Drag coefficient for various surface temperature of NACA0012 airfoil, $\boldsymbol{Re = 20000, K = 3.93, H = 0.0125}$.

4- Conclusion

In this study, impacts of heat transfer on aerodynamic performance of plunging airfoils are analyzed. Hence, the fluid flow is assumed viscous, compressible and unsteady with Re of 20000. Navier-Stokes equations are discretized by FVM and are solved by PIMPLE algorithm. The main findings of the present study can be summarized as follows:

1. For the symmetric airfoil of NACA0012, by 50 k and 100 k reduction of surface temperature than free stream, mean drag coefficient decrease 12.98% and 38.91%, respectively. However this coefficient increases 10.7% and 20.2% by 50 k and 100 k enhancement of surface temperature.
2. In low reduced frequency, vortices pattern is being in drag generation style at all conditions of heat transfer. But by increase in reduced frequency, vortices pattern will be changing in order to produce thrust and drag in cooling and heating conditions, respectively.
3. For the non-symmetric airfoil of NACA4412, heat transfer not only affects the mean and instantaneous drag coefficient but also changes the mean and instantaneous lift coefficient. In addition, in cooling and heating conditions, mean lift to drag ratio increases and decreases 87.8% and 91%, respectively than the condition without heat transfer.