Ferrofluid Thin Films for Airfoil Lift Generation

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In this work, consideration is given to a novel concept for airfoil lift generation and flow control. In this concept, the goal is attained by preventing the growth of the boundary layer from the elimination of the zero slip condition between the surface and the air stream. The concept would simulate all effects of a moving wall leading in the appearance of slip velocity in the gas-fluid interface including the injection of momentum into the boundary layer, with one exception: there is no moving wall but instead a ferrofluid thin film attached at the wall by a magnetic field which permit to attain much more higher velocities at the interface which is not allowable if mobil surface wall are used. Utilizing a simplified physical model for the profile velocity of the ferrofluid film and from ferrohydrodynamic stability considerations an analytical expression for the interfacial velocity was derived. Finally, from the available experimental data on moving walls the expected lift and attack angle enhancement was found. Additional R&D is required in order to explore the possibilities in the use of ferrofluid thin films.

Keywords. Flow separation; Boundary layer; Lift enhancement, Aerodynamics

I. INTRODUCTION

Almost immediately after the Prandtl’s boundary layer theory was proposed, continuous research has been performed in order to find methods to mitigate its negative effects. Despite the large amount of research in methods and strategies for airfoil lift enhancement and control flow as well, however, in all of them the chief goal is to prevent, or at least delay, the detachment of the boundary layer from the wall, [1]-[6]. Among those strategies we have: suction and blowing, turbulence promoters, vortex generator, and moving walls. Suction and blowing methods are intended to remove low energy air, either through suction slots or by blowing high-energy air through backward-directed slots, respectively. Turbulence promoters and vortex generators attempt to control flow separations of symmetric airfoils by creating spots or high turbulence by using some elements such as baffles or wall roughness elements. Finally moving solid walls which are intended to remove the zero slip condition as well as injecting momentum into the boundary layer.

The object of this work was to analyze a novel approach for lift enhancement and flow control. In this concept, the goal is attained by preventing the growth of the boundary layer from the elimination of the zero slip condition between the surface and the air stream. The concept would simulate all effects of a moving wall leading in the appearance of slip velocity in the gas-fluid interface including the injection of momentum into the boundary layer, with one exception: there is no moving wall but instead a ferrofluid thin film attached at the wall by a magnetic field. For this work, suffice is to know that a ferrofluid or ferromagnetic fluid is nothing more than a colloidal liquid that becomes strongly magnetized in the presence of a magnetic field due to presence of nanoscale ferromagnetic, or ferrimagnetic, particles suspended. Fig. 1 shows a pictorially illustration of the core idea proposed in this work.

II. MATERIALS AND METHODS

A. The ferromagnetic thin film layer

To begin with, let us consider Fig. 2 in which a ferrofluid thin film is attached at the wall of an airfoil by a magnetic gradient field normal to the surface which is created by, say, an array of hand-held array of magnets. In addition, the ferrofluid is under the presence of a pumping pressure gradient. We choose the normal coordinates to the surface as $z$–axis and the $x$-axis in the direction of motion of the fluid and also let us assume the origin of coordinates at the wall. Considering that the velocity depends only on $z$, the ferrohydrodynamic Navier-Stokes equation gives, [7]

$$\frac{1}{\eta_f} \frac{\partial p}{\partial x} = \frac{\partial^2 v_x}{\partial z^2} \quad (1)$$

and
\[
\frac{\partial p}{\partial z} = \rho_f g + \mu_f M_z \frac{\partial H}{\partial z} \tag{2}
\]

where \( p \) is pressure; \( v \) is the ferrofluid velocity; \( \eta_f, \rho_f, M_f \) and \( \mu_f \) are the ferrofluid dynamic viscosity, density, magnetization and magnetic momentum, respectively; \( g \) is gravity, and \( \frac{\partial H}{\partial z} \) is the uniform normal magnetic gradient. After integrating Eq.(2) one obtains

\[
p = p_1(x) + \rho_f g z + \mu_f M \frac{\partial H}{\partial z} \tag{3}
\]

Now, we will define the boundary conditions for Eq.(1). First, on the solid boundary the ferrofluid velocity vanishes, it gives us the first condition

\[
v_x(z = 0) = 0 \tag{4}
\]

Second, on the interface air-ferrofluid, \( z = \delta \) the components of a viscous-stress tensor are continuous and then

\[
\eta_f \frac{\partial v_x}{\partial z} \bigg|_{z=\delta} + \eta_a \frac{\partial u_x}{\partial z} \bigg|_{z=\delta} = 0 \tag{5}
\]

where \( u \) and \( \eta_a \) are the air velocity and dynamic viscosity, respectively. For a very thin film \( \delta \to 0 \) and considering that \( \eta_f \gg \eta_a \), then it could be allowable to assume \( \eta_f \frac{\partial v_x}{\partial z} \gg \eta_a \frac{\partial u_x}{\partial z} \) and then Eq.(5) simplify as

\[
\eta_f \frac{\partial v_x}{\partial z} \approx 0 \tag{6}
\]

Finally, the discharge or volumetric flow is given by

\[
Q = \int_0^\delta v_x(z)dz \tag{7}
\]

Taking into account the set of boundary conditions, the solution of Eq.(1) yields

\[
v_x = \frac{3Q}{2\delta} \left[ 2z - \frac{z^2}{\delta} \right] \tag{8}
\]

and the interfacial velocity, \( v_x(z = \delta) = v_i \)

\[
v_i = \frac{3Q}{2\delta} \tag{9}
\]

likewise the mean velocity \( \bar{v}_x \)

\[
\bar{v}_x = \frac{Q}{\delta^2} \tag{10}
\]

which considering Eq.(9) becomes

\[
\bar{v}_x = \frac{2v_i}{3} \tag{11}
\]
B. Film stability

From Eq.(8) one may be tempted to think that by increasing the volumetric flow indefinitely, i.e., the pumping power, or by decreasing the thickness of the film, it could be possible to increase the interface velocity as pleased. However, this is not the case. Actually, the maximum interface velocity is limited by Kelvin-Helmhotz instabilities which arose from the relative motion between the ferrofluid and the air stream. The criterion for instability in the magnetic Kelvin-Helmhotz problem when the ferrofluid film is under the action of a magnetic field is given by, [7]

\[
(v_x - u_o)^2 > \frac{\rho f + \rho a}{\rho f \rho a} \left[ 2 \left( g(\rho f - \rho a) \sigma \right)^{\frac{3}{2}} + \frac{(\mu a - \mu f)^2 H_x^2}{\mu a + \mu f} \right]
\]

(12)

where \(v_x\) is the mean ferrofluid velocity, \(u_o\) the air free stream velocity; \(\rho f\) and \(\rho a\) the density of the ferrofluid and the air, respectively; \(g\) is gravity; \(\sigma\) the surface tension, \(\mu a\) and \(\mu f\) the magnetic permeability of the air and the ferrofluid, respectively. In the above equation, the uniform magnetic field \(H_x\) is the magnetic field collinear with the direction of wave propagation (the stream direction), where it is known that a tangential applied magnetic field in the direction normal to the direction of wave propagation offers no stabilization, [7].

Because \(\rho a \ll \rho f\) and \(\mu a \ll \mu f\), and taking into account Eq.(11), Eq.(12) becomes

\[
\frac{v_i}{u_o} > \frac{3}{2} \left[ 1 + \frac{1}{u_o} \left[ 2 \left( g \frac{\sigma}{\rho f} \right)^{\frac{3}{2}} + \frac{\mu f H_x^2}{\rho a} \right]^{\frac{1}{2}} \right]
\]

(13)

However, despite that a uniform magnetic field normal to the direction of wave propagation provides null stabilization, nevertheless, a magnetic gradient in this direction is causing a normal body force as

\[
F_m = \mu_o M \nabla_z H
\]

(14)

where \(\mu_o\) is the permeability of free space; \(M\) the magnetization of the ferrofluid, and \(\nabla_z H\) is the normal magnetic field. Thus, an effective volumetric acceleration \(g_e\) may be defined by considering both gravity and the magnetic field as

\[
g_e = g + \frac{\mu_o M \nabla_z H}{\rho f}
\]

(15)

Therefore, If only a gradient of magnetic field is acting on the ferrofluid plus gravity and surface tension, the criterion of stability, Eq.(13) becomes

\[
\frac{v_i}{u_o} > \frac{3}{2} \left[ 1 + \frac{1}{u_o} \left[ 2 \left( g \frac{\sigma}{\rho f} \right)^{\frac{3}{2}} + \frac{\mu f H_x^2}{\rho a} \right]^{\frac{1}{2}} \right]
\]

(16)
• Discussion

In order to obtain some idea of the shape of the curves predicted by Eq.(13) and Eq.(16), we assume some typical values of the parameters for a ferrofluid water based: \( \sigma = 70 \times 10^{-3} \text{ N/m}; \) \( g = 9.8 \text{ m/(s}^2\text{)}; \) \( \rho_f = 1.2 \times 10^4 \text{ kg/(m}^3\text{)}; \) \( \rho_o = 1.0 \text{ kg/(m}^3\text{)}; \) \( M = 4.5 \times 10^4 \text{ A/(m)} \), which corresponds to a realizable magnetic field around 0.5 T which can be obtained from a typical hand-held permanent magnet; \( \mu_o = 4\pi \times 10^{-7} \text{ H/(m)}; \) \( \mu_b = 8\mu_o \). The resulting curves are shown in Fig. 3 and Fig. 4 for Eq.(13) and Eq.(16), respectively, and considering practical achievable values for the magnetic field and the magnetic gradient as well.

C. Experimental measurement

In order to obtain the expected lift enhancement and delay of the detachment of the boundary layer by using the proposed ferrofluid thin film technique, one may think that full experiments and design for several airfoils are required. However, fortunately it is not the case, at least for first estimations it is easy to see that from an aerodynamic point of view, there is no any difference if the interfacial velocity is generated by a thin film or a moving solid surface, in other words, a thin film can be regarded as a moving solid surface. At this point, there are substantial experimental measurements available in the literature on the lift enhancement and delay of the detachment (increase attack angle) from moving solid surfaces, therefore, the most important experimental work which must be dedicated to test the ferrofluid thin film concept in the verification of the interfacial velocity attainable, where as previously mentioned, once obtained this interfacial velocity, the lift and angle of attack as well can be obtained for the available literature for specific airfoils using moving surfaces (belt, etc...). With this goal, a set of experiments were performed in order to verify the predicted interfacial velocity derived in preceding section.

Figs. 5 an 6 show the basic configuration for this series of experiments. We have simple square polycarbonate cavity, i.e., \( \delta = l \) with a 170-mm-long and open at the top which was filled with ferrofluid. Below the cavity a train of hand-held neodymium permanent magnets were located in order to attach the ferrofluid at the bottom wall of the polycarbonate cavity. The ferrofluid is then pumped through the cavity by using a peristaltic pump whose flow is regulated electronically by variation of the number of revolution per minute. The experiment was repeated by using several cavities with the same length but with different thickness \( \delta \). The ferrofluid employed was Mn_0.5Zn_0.5Fe_2O_4 in water. The system was located in a wind tunnel where an air free stream was circulating parallel to the cavity. The objective of the experiments was to obtain the interfacial velocity \( v_i \) as function of several parameter (velocity of the air free stream, the inclination and the volumetric flow). The measurement of the air velocity was performed using a Fluke 922 air-flow meter. The magnetic field from the array of magnets was 0.12 T and was measured with a FW BELL 5170 Gauss/Tesla meter.

III. RESULTS AND CONCLUSIONS

The resulting experimental curves are shown in Figs. 7, 8 and 9. Fig. 7 shows the ratio \( \frac{v_i}{u_0} \) as function of the volumetric flow and for several thickness of the cavity. Fig. 8 shows the ratio \( \frac{v_i}{u_0} \) as function of the free stream air; and Fig. 8 it is shown the effect of the angle of inclination of the cavity on the ratio \( \frac{v_i}{u_0} \) and for several thickness of the cavity.

Finally, from the experimental data reported on mov-
ing walls it is possible to assess the lift enhancement and delay of the detachment of the boundary layer (increase of the attack angle), this is because from a purely mechanical point of view, for very thin films, there are no differences if the motion of the interface is produced by a solid moving surface or form a fluid thin film. For illustration, Fig. 10 and Fig. 11 show lift enhancement and the increase of angle of attack for a NACA0015 which is derived form the experimental data on moving walls reported in [8]. The attractiveness of the proposed concept is easily to see by comparing the lift coefficient enhancement as function of $\frac{vi}{uo}$ from Fig. 10, and the allowable $\frac{vi}{uo}$ as function of the air stream velocity from the curves of ferrohydrodynamic stability Fig. 3 and Fig. 4. Thus, as an illustration, a air stream velocity around 100 m/s, will allow for a thin film $\frac{vi}{uo}$ ratios around $\approx 3$ m/s before Kelvin Helmholtz will detach the film. With these ratios, the lift coefficient enhancement could be around 1.8 which is figure of merit to be considered. Additional R&D is required in order to explore the possibilities in the use of ferrofluid thin films.

• Declaration of Interests

The authors report no conflict of interest.

• Availability of data and materials

Not applicable

• Competing interests

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**NOMENCLATURE**

- \(g\) = gravity
- \(H\) = magnetic field
- \(l\) = width of the ferrofluid film
- \(M\) = magnetization
- \(Q\) = volumetric flow
- \(u\) = velocity of air
- \(v\) = velocity of ferrofluid
- \(x\) = length coordinate
- \(z\) = normal coordinate

**Greek symbols**

- \(\delta\) = thickness of the ferrofluid film
- \(\eta\) = dynamic viscosity
- \(\mu\) = magnetic momentum
- \(\rho\) = density
- \(\sigma\) = surface tension

**subscripts**

- \(a\) = air
- \(f\) = ferrofluid
- \(i\) = interface air-ferrofluid

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