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Aqueous Humour Dynamics in Anterior Chamber with the Descemet's Membrane Detachment

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Abstract. Descemet membrane detachment (DMD) develops in the human eye once the aqueous humour (AH) enters the Descemet membrane (DM) space through a break and causes the membrane to separate from the stroma (the main layer of the cornea which is responsible in giving the cornea its strength). A mathematical model of AH flow through the DMD has been developed. The mathematical model is set up to analyze the fluid mechanics concerning the progression of DMD. This model is based on the Naiver-Stokes equations that govern the flow of AH in the anterior chamber (AC). Specifically, fluid flow in the AC is described as a flow driven by buoyancy effects due to the existing temperature different between the cornea and the pupil. A thin flap (DMD) which is kept in contact with a dome shape (cornea) is considered in the flow in order to show how the type of the DMD affect the fluid flow behave in the AC. The relevant fluid flow equations have been solved numerically using finite element method with the aiding of COMSOL Multiphysics. The results have shown that the different type of DMD do affect the characteristics of the fluid flow in the AC.

INTRODUCTION

Descemet membrane (DM) is the layer lies between the stroma and the endothelium layer of the cornea. Descemet membrane detachment (DMD) happens when the DM is separated away from the stroma by the aqueous humour that flows into the space between the membrane and the stroma through a tear or break on the DM. Commonly, the DMD happen during cataract extraction [1]. However, [2-4] reported that the DMD also occur when iridectomy, trabeculectomy, corneal transplantation, deep lamellar keratoplasty, holmium laser sclerostomy, alkali burn and viscocanalostomy. The technique of curing the DMD caused by cataract surgery with sulphur hexafluoride injection was reported by [5]. [1] presented the case of treating the scrolled DMD by injecting fourteen percent of intracameral perfluoropropane (C3F8) into the AC. Generally, DMD can be categorized into planar or non-planar, scrolled or non-scrolled and peripheral or non-peripheral with central cornea involvement [1, 2, 6]. A planar and non-planar DMD are distinguished base on the separation distance between the stoma and the DM. The distance in non-planar DMD is greater than one millimeter while planar DMD is less than one millimeter [2, 6]. The spontaneous reattachment of the detached membrane has been reported in [7-12]. [11] stated that the non-planar detachments were difficult to reattach spontaneously compare to the planar DMD. In contrast, the non-scrolled and non-planar DMD might be able to reattach spontaneously had been concluded in [12]. In addition, [9] concluded that the non-planar and non-scrolled DMD will often spontaneously reattach if given enough time. Recently, [7, 10] stated that the aqueous humour (AH) flow in the AC, which caused by the buoyancy effects due to temperature gradient in the AC, may drive the spontaneous reattachment. This indicate that the different type of the DMD may affect the flow in the AC. Therefore, the aim of this study is to investigate how the different type of the DMD affect the behavior of the flow in AC. In this

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study, we use the fluid mechanical model of flow in AC developed by [10, 13] with the presence of detached DM in the AC to study the fluid flow mathematically. A full complete Naiver-Stokes equations have been used, whereas in [10, 13], a simplified Naiver- Stokes equations was used in order to solve the problem analytically. Finite element method was applied to solve the relevant fluid flow equations and the obtained results have been analyzed.

FORMULATION OF PROBLEM

Model Construction

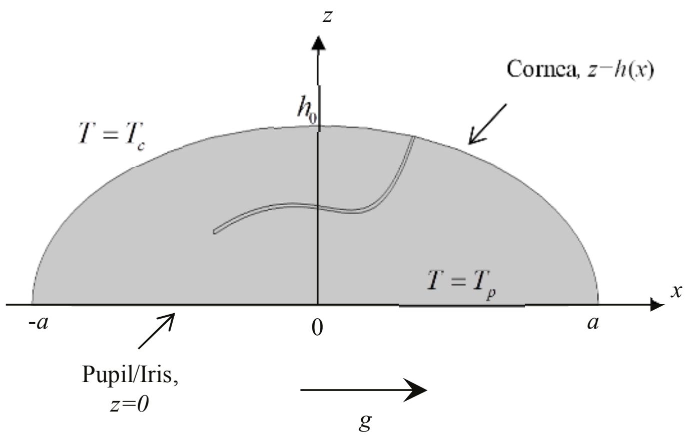

FIGURE 1. Schematic diagram of the DMD in the AC.

A two-dimensional AH flow driven by buoyancy effects in the AC during DMD in the plane y = 0 has been considered, as shown in Fig. 1. The buoyant convection happens due to the temperature gradient that occur across the AC of the eye. The different temperature at the back of the AC, which is close to core body temperature (37 ^{0}C), to the outside of the cornea (say 25 ^{0}C) have induced the temperature gradient. We introduce a Cartesian coordinate system (x, z) which aqueous humour flow between the plane formed by pupil aperture and the iris, z = 0 and the anterior surface of the cornea, $z = h(x)$. At the iris, the temperature is fixed at T_p which is close to the human body temperature, 37 ^{0}C, and the temperature at the cornea is assumed to be T_c, around 24 ^{0}C. The gravity, g is acted along the positive x-axis as shown in Fig. 1 because the patient is assumed to be in an upright position. To be realistic, a set of typical values for human eye is used: h_0=2.75mm, a=5.5mm, the AH has a typical velocity of U=10^{-4}ms^{-1}, $\upsilon = 0.9\times10^{-6}$ m^{2}s^{-1}, gravity, g=9.8ms^{-2} and $\alpha = 3\times10^{-4}$ K^{-1}. The AH is assumed to be Newtonian, viscous and incompressible. A detached DM is assumed to be a thin and small flap attached onto the anterior surface of the cornea. According to the Boussinesq approximation, the governing equations are:

$$
\begin{aligned}
&-\frac{\partial p}{\partial x}+\upsilon\left(\frac{\partial^2 u}{\partial z^2}+\frac{\partial^2 u}{\partial x^2}\right)+g\left(1-\alpha\left(T-T_c\right)\right)=\rho\left(u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}\right),\\
&-\frac{\partial p}{\partial z}+\upsilon\left(\frac{\partial^2 w}{\partial z^2}+\frac{\partial^2 w}{\partial x^2}\right)=\rho\left(u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}\right),\\
&\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0,\qquad \frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial z^2}\right)=u\frac{\partial T}{\partial x}+w\frac{\partial T}{\partial z},
\end{aligned}
\tag{1}
$$

where υ is the kinematic viscosity, ρ is the density, k is the specific heat, C_p is the thermal conductivity, g is the gravity and α is the coefficient of linear thermal expansion of the fluid. We assumed the thermal properties remain constant since the temperature changes involved are small, here, a standard thermal properties of water at blood temperature is used. Therefore, following [10, 13] $\rho = 10^3$ kg m^{-3}, C_P=4200 J kg^{-1}K^{-1} and k=0.57 Wm^{-1}K^{-1} are used. The boundary conditions for the velocity are:

$$\begin{aligned} u(x,0) &= w(x,0) = 0, \\ u(x,h(x)) &= w(x,h(x)) = 0. \end{aligned} \tag{2}$$

The boundary conditions for temperature are as follows:

$$\begin{aligned} T &= T_p \text{ on } z = 0, \\ T &= T_c \text{ on } z = h(x), \end{aligned} \tag{3}$$

where T_c and T_p denote the temperature at the cornea and the plane formed by the pupil and the iris respectively. By assuming that the fluxes and the pressures at each point x are continuous, the pressure is known and is equal to the constant pressure $p = p_a$ at $x = a$.

Computational Mesh and Numerical Method

The governing equations (1) subjected to the boundary conditions (2) and (3) were solved numerically using the finite element method. The commercial software package, COMSOL Multiphysics 5.0 was used to compute the numerical results. All the computation in the study were performed on a personal computer with a processor speed of 2.30 GHz and a RAM of 8GB. The two-dimensional model was meshed using triangular elements and Lagrange quadratic polynomial was used to approximate the temperature along each surface. In order to show that the results do not affected by the total number of elements, a mesh test was conducted. Fig. 2 shows that the numerical results determined by using total number of elements above 1354 have small distinction. Therefore, we hold the view that the results are independent from the number of elements if more than 1500 elements are used. In this research, the geometry was meshed by 3000-4000 elements which generated by the COMSOL Multiphysics and in the system contained 20000-30000 degreed of freedoms.

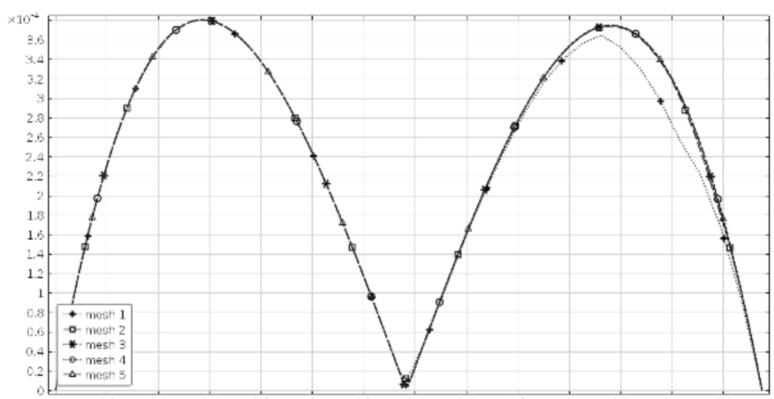

FIGURE 2. Magnitude of the velocity [m/s] along the line (0,0) to (0,0.0275) [m] in the domain with, mesh 1= 416 elements, mesh 2 = 1354 elements, mesh 3 = 2507 elements, mesh 4 =3263 elements and mesh 5 = 5260 elements.

RESULT AND DISCUSSION

The streamline for flow within the AC driven by the buoyancy convection without the existing of DMD is shown in Fig. 3. Figure 3 is alike to the streamline plotted (Fig. 3 in [10] and Fig. 4 in [13]). This illustrate that the numerical result computed in this study have a good agreement with the analytical result obtained in [10] and [13]. Table 1 shows that the results are found to be excellent agreement for the value of maximum speed and the position of the existing of the maximum speed. This great agreement has enhanced our confidence to the numerical results obtained in this paper. Figures 4-7 show the velocity magnitude [m/s] and streamline plots for the cases with the non-scrolled/scrolled, non-planar/planar and non-peripheral/peripheral for lower DMD and upper DMD respectively. In Figs. 4 and 5, the maximum velocity magnitude was changing when different types of DMD were considered. The maximum velocity magnitude for the non-scrolled, planar and peripheral DMD (see Fig. 4(c)) is 3.777×10^{-4} [m/s], whereas the value is decreased to 3.585×10^{-4} [m/s] when non-planar case was considered (see Fig. 4(d)). For non-peripheral cases, the value of the maximum velocity magnitude more reduced (see Fig. 4(a) and Fig. 4(b)). Same phenomena were observed in Fig.5 to Fig. 7. However, for the cases of scrolled DMD, the maximum velocity magnitude is lesser compare to the non-scrolled DMD, for example, the maximum velocity magnitude in Fig.4(b) is 3.041×10^{-4} [m/s] and in Fig.5(b) is 2.034×10^{-4} [m/s]. For a lower DMD (see Fig.4(a)), gravity acts in the positive x-direction. Base on the Bernoulli principle, which states that the pressure is inversely related to fluid velocity the principle, the pressure that act on the detached membrane from the right hand side as shown in Fig.4(a) is higher compare to the left hand side. Therefore, the forces acting to the DMD tends to make the detachment worse. However, for the upper DMD (see Fig.6(a)), the DMD is pushed back to the stroma. This finding is consistent with the results showed in [10]. By the Bernoulli principle, the types of DMD shown in Fig.4(b) and Fig.5(b) are estimated to become worsen. The spontaneous reattachment is predicted to happen for the type of DMD shown in Fig.6(c) and Fig.7(c). For the others types of DMD are hard to conclude, further research is needed to fully understand the real mechanism of the aqueous humour under the effect of DMD and the possibility of the spontaneous reattachment to happen.

TABLE 1. Comparison of the computed numerical result with the analytical result obtained in [10].

Method	Maximum Speed [m/s]	Position [m]
COMSOL, (Present)	3.807×10^{-4}	(0, 0.00564)
Analytical, ([10])	3.962×10^{-4}	(0, 0.00581)

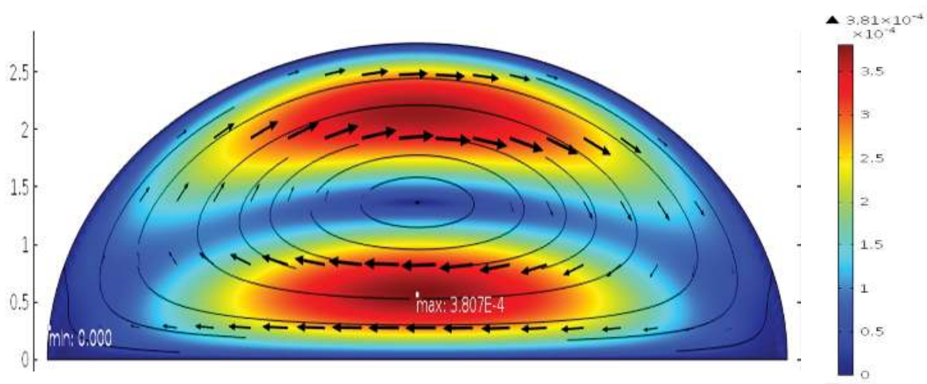

FIGURE 3. Velocity magnitude [m/s] and streamline plots for the case without DMD.

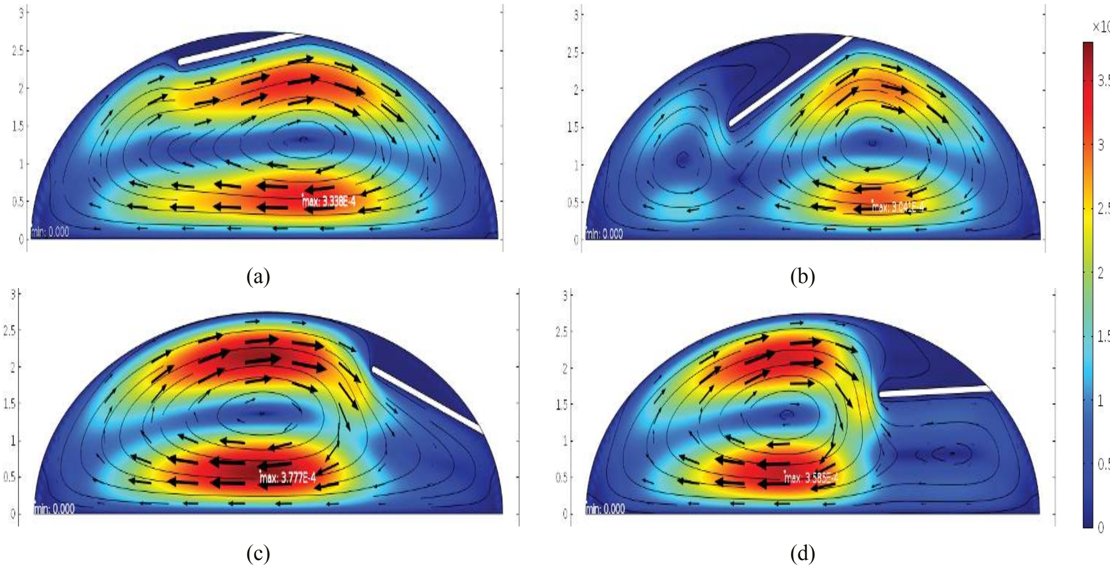

FIGURE 4. Velocity magnitude [m/s] and streamline plots for the case with the non-scrolled (a) planar and non-peripheral, (b) non-planar and non-peripheral, (c) planar and peripheral and (d) non-planar and peripheral, lower DMD.

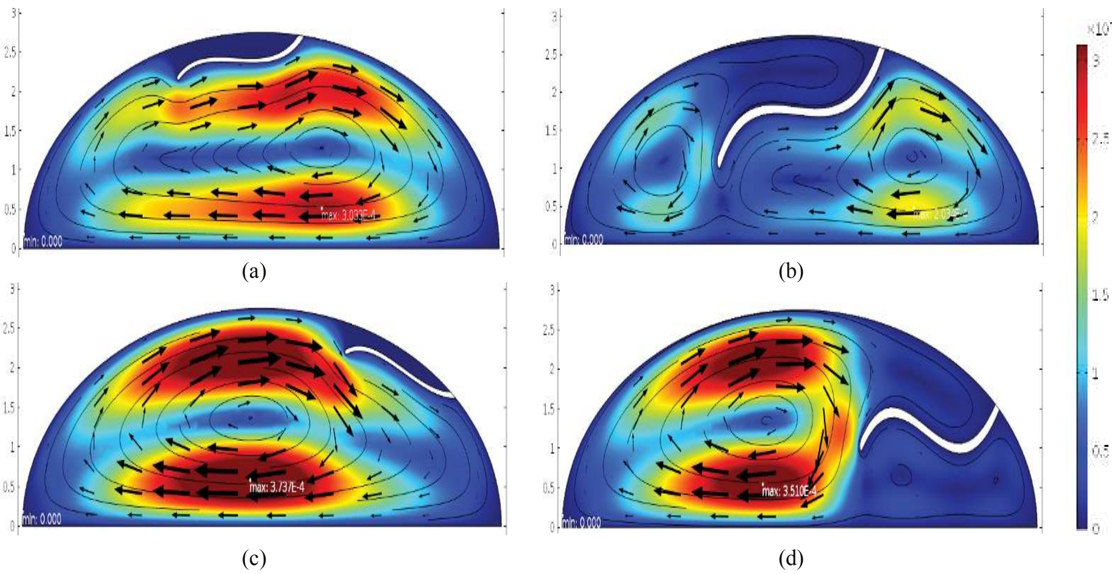

FIGURE 5. Velocity magnitude [m/s] and streamline plots for the case with the scrolled (a) planar and non-peripheral, (b) non-planar and non-peripheral, (c) planar and peripheral and (d) non-planar and peripheral, lower DMD.

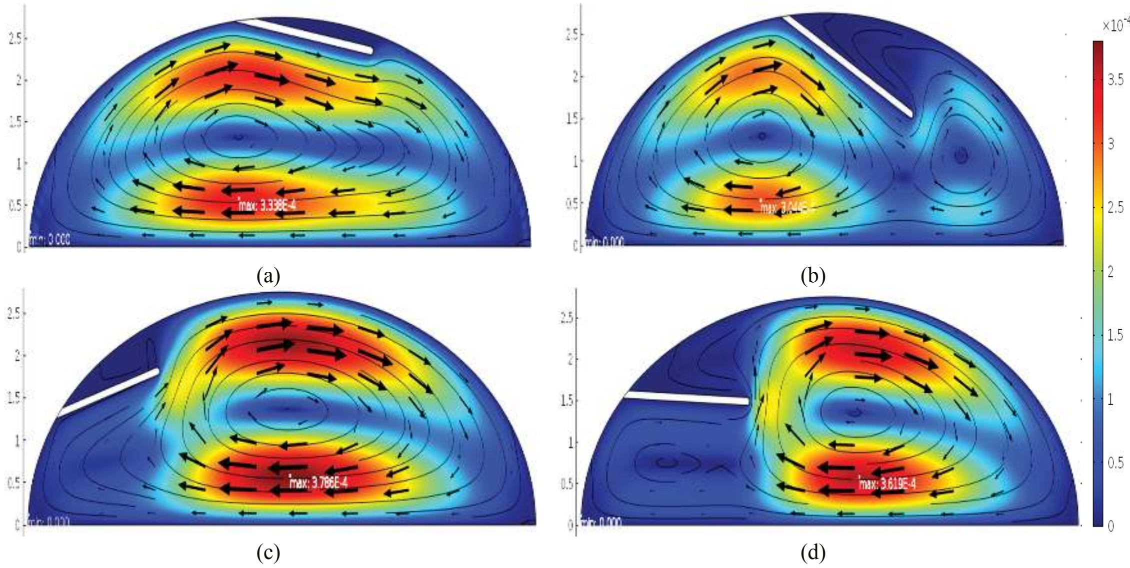

FIGURE 6. Velocity magnitude [m/s] and streamline plots for the case with the non-scrolled (a) planar and non-peripheral, (b) non-planar and non-peripheral, (c) planar and peripheral and (d) non-planar and peripheral, upper DMD.

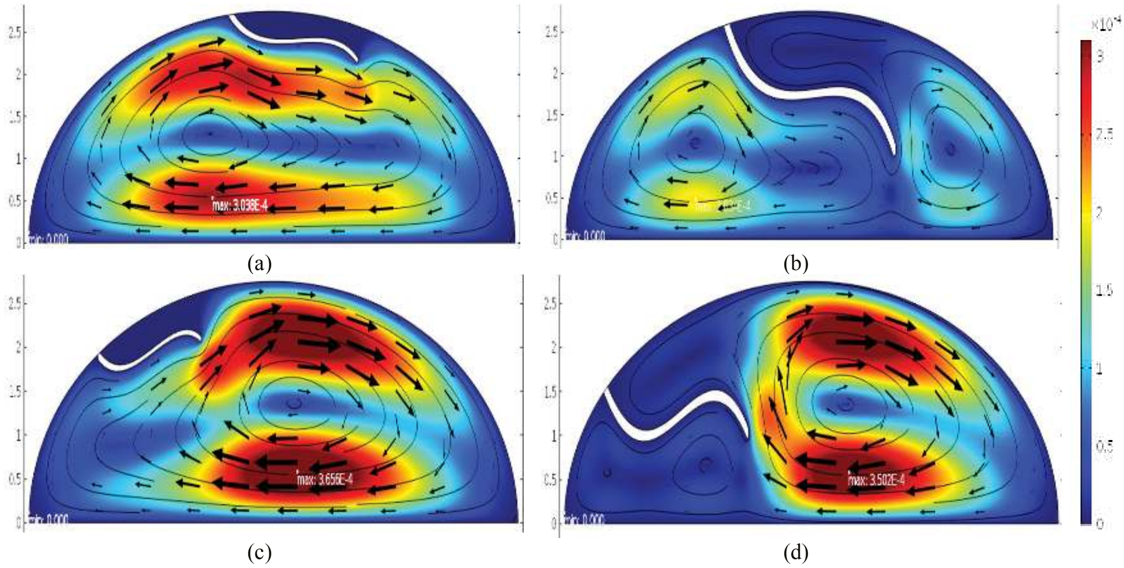

FIGURE 7. Velocity magnitude [m/s] and streamline plots for the case with the scrolled (a) planar and non-peripheral, (b) non-planar and non-peripheral, (c) planar and peripheral and (d) non-planar and peripheral, upper DMD.

SUMMARY

Numerically, the behaviour of the AH flow driven by the buoyancy force through the DMD have been studied. The velocity streamlines and contours for different cases are obtained and plotted. Some interesting finding of the study can be concluded as follows:

1. The maximum speed of the AH is effected by the position and type of the DMD.

2. The spontaneous reattachment of the DMD is tend to happen in case of upper DMD for type of either scrolled or non-scrolled, planar and peripheral (see Fig. 6(c) and Fig. 7(c)).

In our opinion, more research has to be done in order to fully understand the behavior of the AC flow under the types of DMD.

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