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PREDICTION OF THROMBUS FORMATION ON IMPINGING JET FLOW BY EULERIAN COMPUTATIONAL FLUID DYNAMICS (CFD) –EFFECTS OF CONCENTRATION BOUNDARY CONDITIONS ON PLATELET ADHESION–

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Abstract. *For the thrombus formation in medical fluidics, it is considered that stagnation of the flow, shear rate and adhesion on the wall are important physical factors. Affeld et al. suggested that shear rate distribution and particle adhesion distribution on the wall are important factors by their experiment of impinging jet flow with stagnation point, and also showed that adhesion mechanism of platelets on the flow field is also important by theoretical evaluation. However, the effect of platelet adhesion on white thrombus formation by shear flow is still now unknown. In this paper, to improve accuracy of the prediction for platelet adhesion, transport process of concentration on impinging jet flow based on Affeld et al.'s experiment is analyzed by finite difference CFD with modifying the thrombus evaluation model. In addition, distribution of concertation on the wall is tried to be evaluated by setting simple boundary conditions of concertation for platelets adhesion. It is concluded that the distribution of platelet adhesion on the wall surface can be predicted accurately by the proposed evaluation method composed of distribution of concentration, velocity and shear rate with adjusting the threshold.*
Keywords: Computational fluid dynamic (CFD), Thrombus formation, Impinging jet flow, Platelet adhesion

1. **Introduction.** Thrombus formation and hemolysis occur in medical fluidics such as artificial hearts, centrifugal blood pump and stent, and they have been major problems for developing medical fluidics. In general, there are two types of thrombus such as red and white thrombus. It is well known that white thrombus occurs by high shear flow in medical fluidics. In addition, it is also considered that stagnation of flow [1], shear rate and adhesion on the wall are involved physical factors in thrombus formation. For the thrombus formation, it is considered that stagnation of the flow, shear rate and adhesion on the wall are important physical factors such as previous research works [2-5]. As for recent research works for thrombus formation, main discussed points are model based on shear rate, chemical reactions, fibrin network and platelet aggregation [6-12]. However, there are still now no complete models for prediction as the thrombosis itself is a complicated system. Besides, in our previous investigations [13-17], visualization of white

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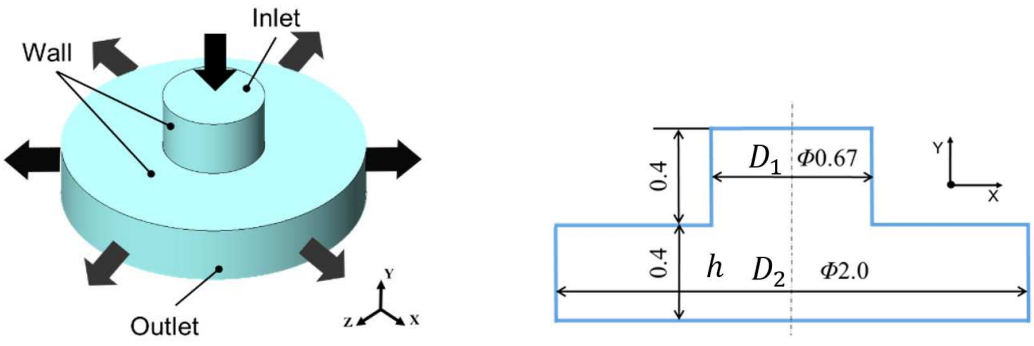
thrombus formation and the flow analysis by computational fluid dynamics (CFD) were done to find out the relation between shear rate and thrombus formation. As results, it was suggested that possibility of thrombus formation and platelet adhesion is high near re-attachment point by orifice pipe where high shear rate occurs, and it was found that possibility of thrombus formation and platelet adhesion is high near re-attachment point of orifice pipe flow [13,16]. On the other hand, Affeld et al. [1] suggested that shear rate distribution and particle adhesion distribution on the wall are important factors by their experiments of impinging jet flow with stagnation point, and also showed that adhesion mechanism of platelets on the flow field is also important by theoretical evaluation. However, the effect of platelet adhesion on white thrombus formation by shear flow is still now unknown. Nakata et al. analyzed the model of Affeld et al.'s experiment by Navier-Stokes equations with discrete particle motions, but could not accurately predict the adhesion distribution of platelets on the wall [17]. Especially outside of impinging jet flow, the number of platelet adhesion was more than that in the experiment by the discrete particle model due to the inertia of discrete particles. Then it is necessary to develop a new model for platelet adhesion by finite difference method with consideration of concentration instead of particle model.

In this paper, to improve accuracy of the prediction for platelet adhesion, transport process of concentration on impinging jet flow based on Affeld et al.'s experiment is analyzed by finite difference CFD with modifying the thrombus evaluation model. In addition, distribution of concertation on the wall is tried to be evaluated by setting simple boundary conditions of concertation for platelets adhesion.

As for chapters in this paper, computational object and methods to find out the effects of modeling boundary conditions of concertation for platelet adhesion on the prediction accuracy is shown in Section 2, the CFD results and related comparisons are shown and discussed in Section 3, and the concluding remarks are described in Section 4.

2. **Computational Object and Methods.** Figure 1 shows the analysis model of the impinging jet flow, Figure 1(a) shows the an overall view of the model and Figure 1(b) shows a section view. The object model has the same geometry used in the experiment by Affeld et al. [1]. In this case, inlet diameter of the model is $D_1 = 0.67$ [mm], bottom surface diameter is $D_2 = 2.0$ [mm] and the distance from upper surface to bottom surface is $h = 0.4$ [mm].

This geometry including the size is typical impinging jet flow chamber to mimic the medical fluidics.



(a) Overall view (b) Sectional view

FIGURE 1. Geometry of flow chamber

In this study, ANSYS Fluent 18.2 (Fluent) is used as finite volume method. The number of meshes is approximately 470,000 in this model, and the refined meshes are concentrated near the wall.

The flow is dealt as laminar because the order of Reynolds number is 10. Governing equations are the continuity equation and incompressible Navier-Stokes equations as follows:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\left(\frac{\partial^2 u_i}{\partial x_j^2}\right) \tag{2}$$

where $i = 1, 2, 3$, and x_1, x_2, x_3 indicate x, y, z respectively. u_1, u_2, u_3 mean u, v, w that are velocities of x, y and z directions. And ρ is density, p is pressure and v is coefficient of kinematic viscosity. In addition to these equations, the transport equation of concentration is used to investigate the concentration distribution as follows:

$$\frac{\partial c}{\partial t} + \frac{\partial (c u_i)}{\partial x_j} = \lambda \frac{\partial^2 c}{\partial x_j^2} \tag{3}$$

where c is concentration, and λ is diffusion coefficient.

As for this analysis, it is based on the fundamental equations of concentration shown in Equation (3) and the effects of the chemical reaction and thrombus formation of the substance are not considered, and only the transport process of concentration of a single substance is analyzed.

Actually physical properties of the plasma water are as follows: Density $\rho = 1000$ [kg/m^3], viscosity $\mu = 1.3 \times 10^{-3}$ [kg/m·s] and diffusion coefficient $\lambda = 1.58 \times 10^{-9}$ [cm^{2}s^{-1}]. Here density and viscosity values of the plasma are the same ones as that used in the Affeld et al.'s paper [1], and the diffusion coefficient is the same as that is used in the numerical analysis by Yi et al. [15] in which the model of platelet deposition and activation was developed.

In this analysis, transient calculation is done with time step $\Delta t = 0.25$ [s] until $t = 10.0$ [s]. Boundary conditions for CFD are the same as Affeld et al.'s experiments, in which mass flow rate $Q_{in} = 5.55$ [mm^3/s] or velocity $u_{in} = 15.8 \times 10^{-3}$ [m/s] for inlet, static pressure is 0 [Pa] for outlet and non-slip velocity for wall. Boundary conditions of concentration are that concentration $c_{in} = 2.0 \times 10^8$ [1/ml] for inlet, concentration flux is 0 for outlet as shown in Figure 2. In this figure, R means radius of the flow chamber, r means r-coordinate on the polar coordinate system from the center of flow chamber. In

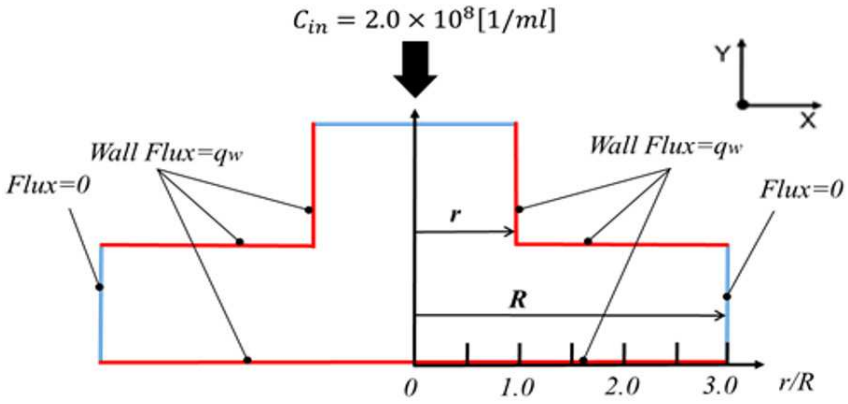


FIGURE 2. Boundary conditions for concentration

this study, to simulate platelet adhesion on the wall, the concentration flux for walls is modeled as follows:

$$J = k_{rs} \times c \tag{4}$$

where J is concentration flux in which concentration passes through a unit area per unit time, k_{rs} is adhesion coefficient whose value is 3.7×10^{-5} [m/s] [8] and c is concentration near the wall. Also, the direction of concentration flux is normal vector from bottom surface to flow fluid area. This boundary condition using Equation (4) is newly advanced point to simulate adhesion process by comparing with previous works. Then platelet adhesion distribution is simulated by concentration adhesion distribution because J is variable on each cell.

3. Results and Discussions.

3.1. Evaluation of concentration field and comparison with Affeld et al.'s experiment.

Figure 3 shows normalized concentration distribution by impinging jet flow on the bottom surface. It is found that the concentration value on bottom surface is increasing and it is diffusing to radial direction by convection with time. And related concentration adhesion is considered to be increasing. To obtain adhered concentration distribution on radial direction, the bottom surface is divided in radial direction like ring belt and the amount of the concentration is obtained by integrating with each divided surface. The adhered concentration distribution $c_d(r)$ is evaluated as follows [8]:

$$c_d(r) = \frac{\int_A \int_0^t (k_{as} c(r)) dt dA}{2\pi r \Delta r} \tag{5}$$

where k_{as} is reaction coefficient whose value is 4.6×10^{-5} [m/s], $c(r)$ is concentration at each mesh, t is computational time, Δr is evaluated size and A is surface area on each mesh. In this paper, Δr is fixed to be $R/24$. Figure 4 shows the adhered concentration distribution on radial direction. Figure 4(a) indicates CFD result and Figure 4(b) indicates Affeld et al.'s experimental results.

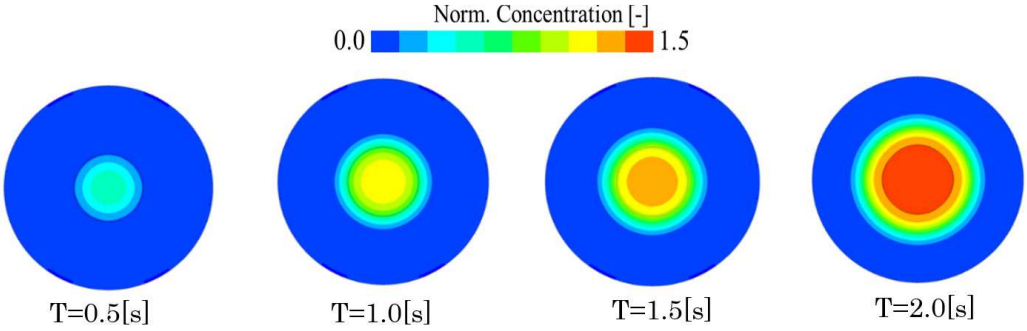
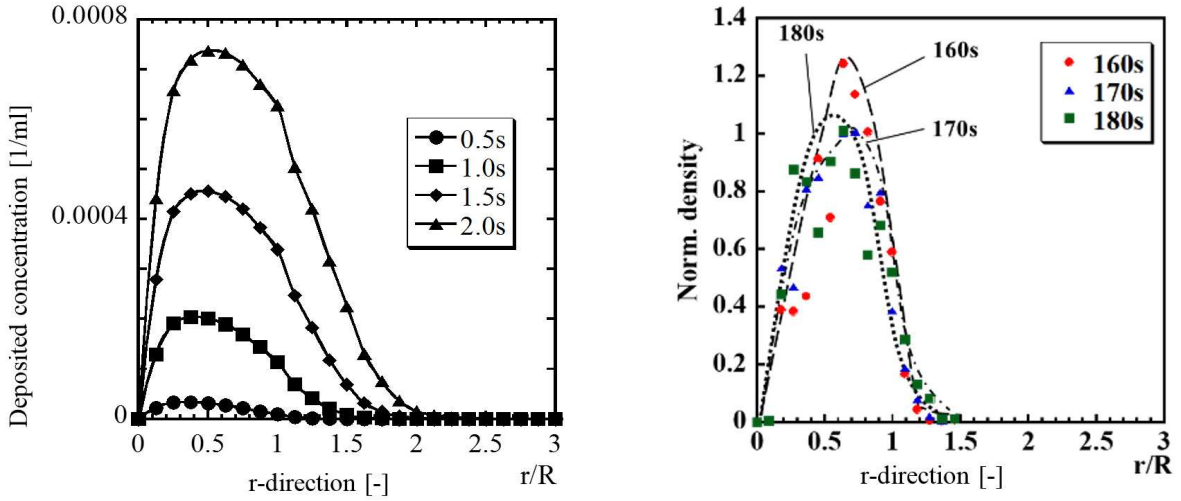


FIGURE 3. (color online) Concentration distribution history

As for the experiment, the following process was done by Affeld et al.: 1) Plasma water with heparin suppressing platelet activation is flown to the device, 2) adenosine diphosphate is added to the circuit at 240 seconds for neutralization of the inhibition in the chemical reaction, and 3) the distribution of the platelet particles adhered to the bottom surface is observed on the microscopic plate. The platelet distribution on the bottom wall is obtained at each time as shown in Figure 4(b).

Comparing the CFD result with the experimental result, it is found that the concentration distribution of CFD result does not agree well with that of experiment on the radial direction because the platelet accumulation outside of $r/R = 1.5$ is hardly seen in



(a) Concentration distribution by CFD

(b) Particle distribution by Affeld et al.'s experiment [1]

FIGURE 4. Comparison between CFD and experiment

the experimental results. The reason is considered that some platelets are adhered on the wall surface and the non-adhered platelets are shed by convection when the amount of adhesion is evaluated by Equation (5).

Even if there is no special treatment of velocity threshold, it is found that the distribution of concentration adhesion can be predicted qualitatively by the concentration boundary condition for the wall surface. To predict more accurately, it is necessary to consider the effects of non-adhered platelets on the amount of adhered platelet concentration by the evaluation method including the threshold of velocity as described in the following subsection.

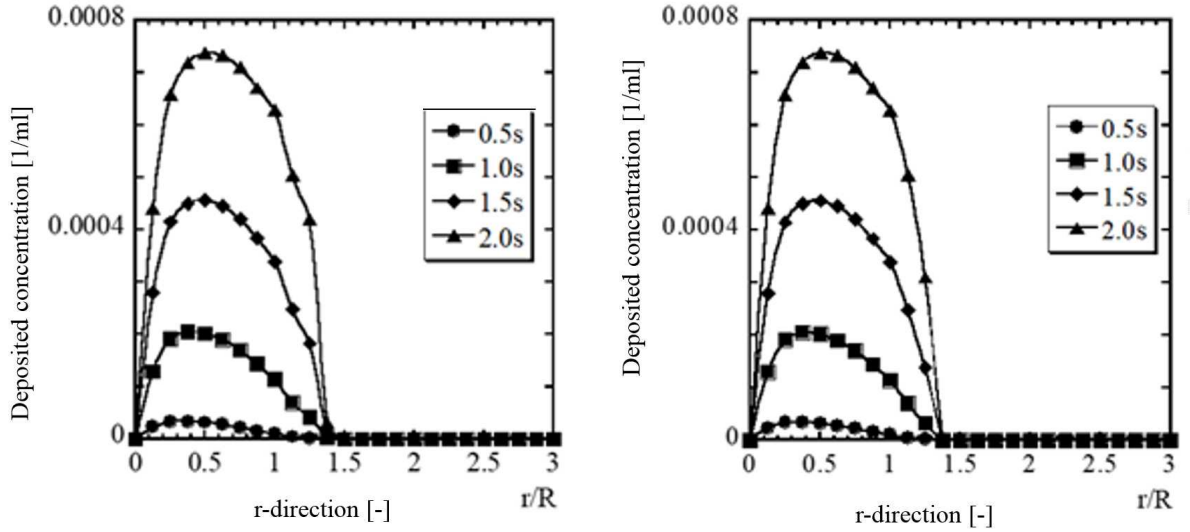
3.2. **Evaluation of concentration distribution with adhesion.** It is considered that platelets are continuously adhered to the bottom surface when the fluid flow partially collides with the bottom surface. Assuming that platelets would continue to be adhered where the velocity v in the y direction is less than the threshold, the threshold values of the velocity v for the following evaluation can be set. Thus, a newly evaluation method for calculating the accumulated amount of adhered platelet concentration at each time can be proposed as follows:

$$c'_d(r) = \frac{\int_A \int_0^t (k_{as} c'(r))\, dt dA}{2\pi r \Delta r} \tag{6}$$

$$c'(r) = \begin{cases} -\text{sign}(v(r) - |v(r)|)c(r), & v < v_{th} \\ 0, & v > v_{th} \end{cases} \tag{7}$$

where the density value $c'(r)$ on the arbitrary region is changed by the threshold v_{th}. Equation (7) shows that the concentration at that location is taken as the adhered concentration if the velocity v is smaller than the threshold value. It means that the concentration is flown by convection and the shed one is excluded when v is larger than the threshold.

Figure 5 shows the radial distribution of the amount of adhered platelets concentration by using Equations (6) and (7). Figure 5(a) indicates the case of $v_{th} = 0$. Figure 5(b) indicates the case of $v_{th} = 0.1 v_{\max}$, where $v_{\max}$ is the maximum negative velocity in the y



(a) $v_{th} = 0$ (b) $v_{th} = 0.1v_{\max}$

FIGURE 5. Concentration distribution by using threshold v_{th}

direction near the wall. From these figures, the amount of adhered platelet concentration is accumulated until $r/R = 1.25$, and it becomes 0 at $r/R = 1.375$. Comparing the result of threshold $v_{th} = 0$ with $v_{th} = 0.1v_{\max}$, it is found that the value of $r/R = 1.25$ in case of $v_{th} = 0.1v_{\max}$ at each time is more than that in case of $v_{th} = 0$. The reason why it is more is that platelet adhesion of $v_{th} = 0.1v_{\max}$ is more likely to occur than that of $v_{th} = 0$.

The distributions of platelet adhesion of these two conditions are also compared with the experimental results in Figure 4(b). It is found that the distribution of the adhesion of experiment is sharper than them. Then the platelet adhesion can be predicted better by adjusting the threshold v_{th} between $v_{th} = 0$ and $v_{th} = 0.1v_{\max}$. However, to predict more accurately, it is necessary to consider the factor such as shear stress as described in the next subsection.

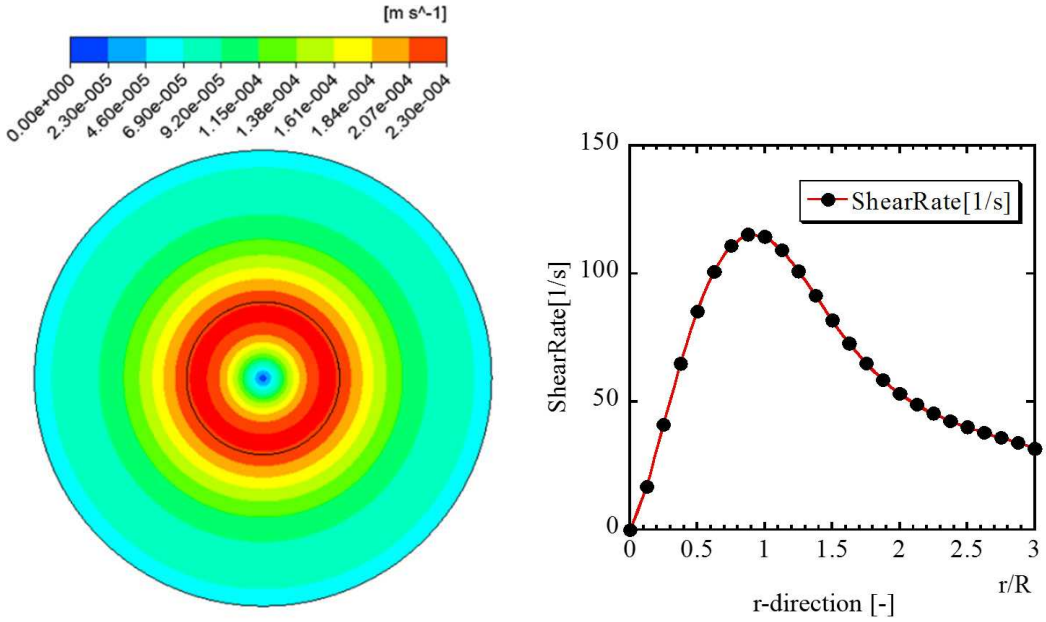
3.3. **Effects of shear rate on concentration distribution.** Affeld et al. also investigated platelet adhesion by theoretical analysis of the flow, and it was suggested that there is a relationship between the shear rate distribution on the bottom surface and the amount of platelet accumulation in the radial direction. Figure 6 shows distribution of shear rate and concentration on the bottom surface by using velocity profile of impinging jet flow. Figure 6(a) shows contour of shear rate, and Figure 6(b) shows radial distribution of shear rate. Considering this result, the additional evaluation method for the accumulated amount of adhered platelet concentration at each time can be also proposed as follows:

$$c''_d(r) = \frac{\int_A \int_0^t (k_{as} c''(r))\, dtdA}{2\pi r \Delta r} \tag{8}$$

$$c''(r) = \begin{cases} -\text{sign}(v(r) - |v(r)|)c(r)D(r), & v < v_{th} \\ 0, & v > v_{th} \end{cases} \tag{9}$$

where $D(r)$ is the shear rate.

Figure 7 shows the distribution of the concentration in the radial direction when the threshold value is $v_{th} = 0.1v_{\max}$ by using Equations (8) and (9). From this result, the concentration with consideration of the shear rate more fit to experiment (Figure 4(b)) without consideration of shear rate (Figure 5(b)) using Equations (6) to (7) when the



(a) Contour of shear rate (b) Radial distribution of shear rate

FIGURE 6. (color online) Distribution of shear rate and concentration on the bottom surface

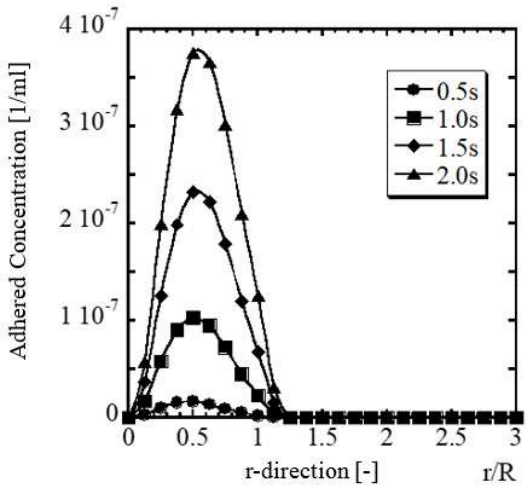


FIGURE 7. Deposited distribution of concentration with consideration of shear rate and velocity on y-axis

threshold value is the same. Therefore, the region where the concentration easily adhered can be predicted by both the velocity in the y direction and the shear velocity.

Figure 8 shows previous results [17] by the discrete particle model, that is distribution of normalized number density along radial direction. Comparing with this previous result, outside of impinging jet flow, the concentration distribution agrees with that in the experiment. The reason why the new results agree with the experiment well is that this method evaluate adhesion effects of platelet on the wall and transport process of high concentration are more properly set by comparing with the discrete particle model. It means that the newly proposed method composed of distribution of concentration, velocity and shear rate with adjusting the threshold will be effective tool for the prediction of

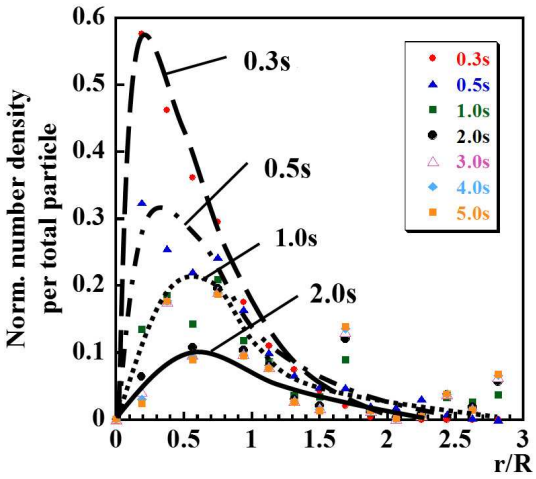


FIGURE 8. Previous results by the discrete particle model: Distribution of normalized number density along radial direction r [Ref. 17, Figure 7]

platelet adhesion process. This evaluation technique can be applied to analyze impinging jet flow for removing adhered algae from the wall in the industrial field.

4. **Conclusions.** In this paper, to investigate the effect of the concentration boundary conditions and the platelet adhesion on the thrombus evaluation, the impingement jet flow with a stagnation point was analyzed by numerical method. The following things are concluded.

1) The concentration boundary conditions for the wall surface can be used to predict the adhered concentration distribution qualitatively.
2) The distribution of platelet adhesion on the wall surface can be predicted more accurately than that in the previous predicted results by the proposed evaluation method composed of distribution of concentration, velocity and shear rate with adjusting the threshold.

In future works, the aggregation process of platelets will be included in this impinging jet flow, and chemical reaction including coagulation process will be considered for this model. This extended investigation can be applied for the prediction of thrombus at the impinging flow such as artificial valves and other high shear flows. In addition, it also can be applied to removing adhered algae from the wall.

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