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Development of Numerical Method for Mass Transfer across the Moving Membrane with Selective Permeability: Approximation of the Membrane Shape by Level Set Method for Numerical Integral

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Abstract : Biological membranes have selective permeability, and the capsules or cells enclosed by the membrane show the deformation by the osmotic flow. This mass transport phenomenon is observed everywhere in a living body. For the understanding of the mass transfer in a body, it is necessary to consider the mass transfer phenomenon across the membrane as well as the deformation of the membrane by a flow. To our knowledge, in the numerical analysis, the method for mass transfer across the moving membrane has not been established due to the difficulty of the treating of the mass flux permeating through the moving membrane with selective permeability. In the existing methods for the mass transfer across the membrane, the approximate delta function is used to communicate the quantities on the interface. The methods can reproduce the permeation of the solute, but cannot reproduce the non-permeation. Moreover, the computational accuracy decreases with decreasing of the permeable coefficient of the membrane. This study aims to develop the numerical method capable of treating three-dimensional problems of mass transfer across the moving flexible membrane. One of the authors developed the numerical method with high accuracy based on the finite element method. This method can capture the discontinuity on the membrane sharply due to the consideration of the jumps in concentration and concentration gradient in the finite element discretization. The formulation of the method takes into account the membrane movement, and both permeable and non-permeable membranes can be treated. However, searching the cross points of the membrane and fluid element boundaries and splitting the fluid element into sub-elements are needed for the numerical integral. Therefore, cumbersome operation is required for a three-dimensional problem. In this paper, we proposed an improved method to avoid the search and split operations, and confirmed its effectiveness. The membrane shape was treated implicitly by introducing the level set function. As the construction of the level set function, the membrane shape in one fluid element was expressed by the shape function of the finite element method. By the numerical experiment, it was found that the shape function with third order appropriately reproduces the membrane shapes. The same level of accuracy compared with the previous method using search and split operations was achieved by using a number of sampling points of the numerical integral. The effectiveness of the method was confirmed by solving several model problems.

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