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Fluid Dynamics and Transport Phenomena

Power consumption and flow field characteristics of a coaxial mixer with a double inner impeller☆

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ABSTRACT

A coaxial mixer meeting the actual demand of a system with high and variable viscosity is investigated. It has an outer wall-scraping frame and a double inner impeller consisting of a four-pitched-blade turbine and Rushton turbine. The power consumption and flow field characteristics of the coaxial mixer in laminar and transitional flow are simulated numerically, and then the distribution of velocity field, shear rate and mass flow rate are analyzed. The simulation results indicate that the outer frame has little effect on the power consumption of the double inner impeller whether in laminar or transitional flow, whereas the inner combined impeller has a great effect on the power consumption of the outer frame. Compared with the single rotation mode, the power consumption of the outer frame will decrease in co-rotation mode and increase in counter-rotation mode. The velocity, shear rate and mass flow rate are relatively high near the inner impeller in all operating modes, and only under double-shaft agitation will the mixing performance near the free surface be improved. In addition, these distributions in the co-rotation and counter-rotation modes show little difference, but the co-rotation mode is recommended for the advantage of low power consumption.

1. Introduction

Mixing is widely used in chemical, petrochemical, pharmaceutical, food, metallurgical, paper and sewage treatment industries. It plays a significant role in unit operations like homogenization, emulsification, fermentation, crystallization and polymerization [1]. As the core part of a mixing vessel, the agitator directly determines the mixing effect and power consumption of the mixing system, thus influences the quality of the product and the production cost. Therefore, it is meaningful to develop a new- and high-efficiency agitator.

Most traditional agitators have only one type of impeller with the advantages of simple geometry, easy operation and mature design methods, which can meet the needs of most industrial processes. However, single-shaft mixers are usually adaptable to limited and specific technological processes. Actual chemical processes are complex. Firstly, under actual conditions, phase transition, heat transfer and viscosity changes happen simultaneously in chemical reaction processes. For example, at the beginning of the process of producing high-purified formic acid and sodium tripolyphosphate through the polyphosphate acidification of sodium formate, viscosity of the material in the mixing tank is high, but it decreases as the process goes on with the flow property of the mixing system improved [2]. For systems with high and variable viscosity, traditional single-shaft mixers are difficult to satisfy the need to agitation at different stages with changing viscosities. Secondly, single-shaft agitators can usually achieve a single function. Radial flow agitators are good at shearing and beneficial to the turbulent diffusion with the disadvantage of long mixing time and bad global mixing effect [3]. Axial flow agitators can strengthen axial flow of materials with the circulation of the mixed system, but its shearing effect and local mixing effect are relatively poor [4,5]. Thus, coaxial mixers are being developed to meet the different needs at different mixing stages of some industrial processes.

Coaxial mixers can satisfy the different mixing stages of systems with high viscosity. Because of its complex geometry and the space–time variable viscosity, there are quite few reports on its mixing performance [6]. The earliest work was reported by Schneider and Todtenhaupt of EKATO Company [7]. Afterwards, Canadian Tanguy's group did systematic researches on the performance of coaxial mixers, which were composed of an anchor agitator and Rushton turbine impeller or Sevin propeller or Deflo–Sevin impeller [8–11]. Their studies were mainly focused on the influences of rotation modes and speed ratios on power consumption and mixing performance. Some researchers in China also researched on coaxial mixers in recent years [12–15]. Earlier researches were mainly focused on coaxial mixers with only single inner impellers, but it is well known that coaxial mixers with composite inner impellers are more advantageous in those occasions with high and variable viscosity [16]. This paper is about a coaxial mixer, which has an outer wall-scraping frame and a double inner impeller consisting of a four-pitched-blade turbine (abbreviated as PBT-4) and Rushton turbine (abbreviated as RT-6).

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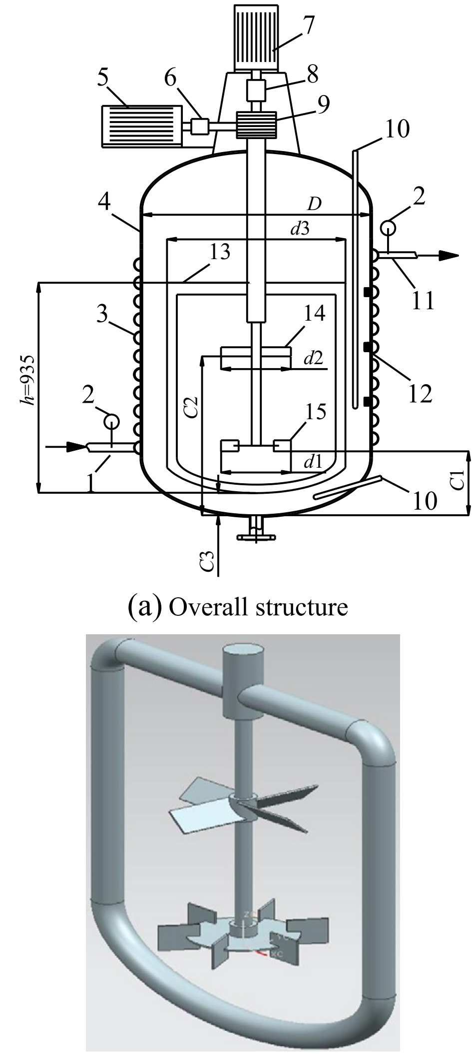
2. Experimental

The schematic of the mixing tank which contains a semicircle spiral jacket and 2 ellipsoidal heads is shown in Fig. 1. The vessel diameter D is 1000 mm, the overall height H is 1500 mm, and the height of liquid h_l is 1050 mm. The central coaxial mixer is composed of an inner high-speed impeller and an outer low-speed impeller. The inner impeller has 2 stirrers, whose upper part is PBT-4 and lower part is RT-6 as shown in Fig. 1(b). The outer impeller is a frame paddle. Specific size is shown in Table 1. This coaxial mixer has two independent driving systems. The speed of the agitator can be adjusted by controlling the frequency of the driving system. Four operating modes, namely, single rotation of either inner or outer impeller, co-rotation and counter-rotation of two impellers, can be achieved.

Coaxial mixers are desirable in systems with high and variable viscosity, and the high-viscosity maltose syrup is selected as the experimental material. Maltose syrup with the concentration of 80%, purchased from Hangzhou Zixiang Co., is colorless, tasteless and non-toxic. And it is a typical Newtonian fluid. The numerical simulation is performed at constant temperature of 28.1 °C. Under such conditions, the viscosity of the material is 10.01 Pa·s and the density 1376.54 kg·m^{-3}.



(a) Overall structure

(b) Coaxial mixer

Fig. 1. Structure of the coaxial mixer. 1- jacket entrance; 2- thermometer; 3- jacket; 4- tank body; 5- electromotor of outer impeller; 6- torque sensor of outer impeller; 7- electromotor of inner impeller; 8- torque sensor of inner impeller; 9- agitator drive or gearbox;10- thermocouple; 11- jacket exit; 12- thermal resistance; 13- frame paddle; 14- PBT-4; and 15- RT-6.

Table 1
Main size parameters of coaxial mixer

Impeller type	RT-6	PBT-4	Frame
Impeller diameter, d/mm	334	334	900
Blade width, w/mm	67	67	65
Blade thickness, e/mm	4	4	65
Distance from the tank bottom, C/mm	250	610	50

3. Computational

3.1. Finite element model

In order to get detailed information, the power consumption and flow characteristics were analyzed with the help of Fluent, a CFD numerical simulation tool. As the simulation is focused on the power consumption and flow characteristics of the fluid and does not involve heat transfer, the jacket and elliptical head are ignored when modeling. The entire flow region is divided into three regions: the inner impeller region, the outer impeller region and the other region. Considering the complex geometry of the coaxial mixer, the tetrahedral elements are selected to mesh each region and the size function is used to refine the grid of the impeller region. Based on these conditions, the appropriate number of cells is determined as 1259914 through grid independence test. Specific meshing is shown in Fig. 2.

The upper surface, assumed as always flat, of the material in the mixing tank is set as free surface, whose normal velocity is zero. Faces of the tank wall, shaft and impellers are all no-slippage wall boundaries. The speed of the shaft and the impellers are particularly specified. The inner impeller region and the outer impeller region belong to the moving region and the other region is static, so the momentum interactions among the three regions are transferred across the interfaces. The coordinate systems of the moving regions rotate at the same speed as that of the corresponding rotating shaft.

3.2. Numerical simulation method

A laminar flow model is chosen for calculation according to the operating conditions. As a result, controlling equations composed of the continuity equation and momentum equations are enclosed [17].

MRF which uses two reference frames for calculation is adopted in calculating the flow field. Impeller regions (moving region) use a reference frame rotating in the same speed as that of the corresponding impeller. Other regions (static regions) use a static reference frame to calculate the flow field. Coupling of pressure and speed is done by means of SIMPLE algorithm. The momentum equation is discretized with second order upwind scheme [18,19].

4. Analysis and Discussion

4.1. Verification of numerical simulation

In order to test the reliability of the numerical simulation, it is necessary to compare the result of the numerical simulation with the experimental data. The experiment is conducted in a stainless agitator vessel, which has the same geometry as described in Section 2. The power consumption of the double inner impeller rotating alone in the experiment is compared with that from the simulation, both having the outer impeller present but stationary, and the detailed information is