*Research Article*

# Development of a Mixing Process Using an HB-Type Impeller to Easily Achieve Scale-Up by Maintaining Geometrical Similarity

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In recent years, a novel home base-type (HB-type) impeller was developed to be based on observation of the streak line pattern. An HB impeller must be simple, speedy, and stable (3S). When an HB impeller is used on the laboratory beaker scale, the mixing performance of the HB impeller is better than that of a normal cylindrical stirring bar. In addition, an industrial-scale HB impeller has been constructed based on the observation of the streak line and isolated mixing regions in the vessel. The present authors believe that scale-up of the mixing process is very easy because the geometrical shape of the impeller can be kept consistent when scaling up from the laboratory scale to the industrial scale.

## 1. Introduction

Although numerous engineering data and mixing processes have been reported, successful scale-up of the mixing process has been very difficult because the design and operation of mixing process involve numerous parameters.

There are a number of basic scale-up rules for mixing processes, including constant power consumption per unit volume, constant impeller tip speed, constant heat transfer coefficient, constant mass transfer volumetric coefficient, and constant just suspension rotational impeller speed. One of the difficult points in scale-up of the mixing process is that when we prioritize a controlling parameter, doing so may adversely impact other parameters. When the Reynolds number is constant for a small-scale or large-scale mixing vessel, the power consumption per unit volume cannot be kept constant. Therefore, if the same physical property of a material is used for industrial production, it is impossible to reproduce the same phenomenon perfectly at a laboratory scale. When scale-up from a laboratory process to an industrial process is carried out, the geometrical similarity

generally cannot be maintained. For example, when a cylindrical magnetic stirring bar is used for small-scale processes in the laboratory, a mixing vessel with a paddle impeller may be used for the corresponding large-scale industrial process. In addition, a number of mixing impellers, such as paddle, turbine, propeller, anchor, helical ribbon, and a number of novel large-paddle impellers, have been developed.

In recent years, several large-paddle impellers, including Maxblend (MB), Fullzone (FZ), Supermix MR205 (MR205), Sammeler (SM), Hi-F mixer (HiF), and Bendleaf (BL), were developed by Japanese companies [1–3]. These impellers are very useful under a wide range of Reynolds numbers.

Inoue et al. [4] suggested a streak line theory to estimate the performance of the mixing vessel and concluded that the streak line pattern was an indication of the mixing. In the previous papers, authors found the important mixing performance of various large-paddle impellers using the streak line visualization method proposed by Inoue et al. In addition, the liquid height was found to be a very important factor when the MB and FZ impellers were used in the laminar region.

The present authors developed a new home base-type (HB-type) impeller, a designation based on the shape of the home plate used in baseball, used under a wide range of Reynolds numbers, as shown in Figure 1 [5]. The HB-type impeller must be simple, speedy, and stable (3S). (1) Simple: since the impeller geometry is very simple, washing the impeller is easy and the production cost is low. The HB impeller is suitable for small-lot production of numerous products. (2) Speedy: the mixing time is very short. (3) Stable: the streak line pattern is stable under a wide range of Reynolds numbers. Even if the liquid height has changed, the HB impeller has demonstrated stable, good mixing performance.

The present authors developed a mixing process using an HB-type impeller for a laboratory scale, a pilot scale, and an industrial scale. In the present paper, authors demonstrate the mixing performance of the HB impeller and the scale-up system of the mixing process using the HB impeller.

## 2. Experimental

Two types of mixing vessels without baffles were used for the pilot scale vessel. When the streak line was observed, the vessel diameter was 0.150 m, and the impeller was made with an acrylic resin. When the mixing process was observed, the vessel diameter was 0.185 m, and the impellers used in flat and dished bottoms were made with stainless steel. The mixing fluid was a starch syrup solution, which was filled to a height equal to the vessel diameter ($H = D$). The power consumption was measured by the shaft torque measurement method using a torque meter (ST-3000, SATAKE Ltd.). The streak lines were visualized by uranine, and the mixing process was visualized by an iodine decoloration reaction.

The experimental visualization of streak line was conducted by uranine solution and a planar laser light. 0.025 g of uranine powder was dissolved into 100 ml of the starch syrup solution to prepare the same viscosity solution as the mixing fluid. The uranine solution was injected at an impeller tip through the impeller hollow shaft. The uranine solution was vertically illuminated by the planar laser light to observe streak line.

The decoloration experiment was based on the oxidation-reduction reaction. Sodium thiosulfate and iodine were adopted as oxidation and reduction agent, respectively. Sodium thiosulfate and iodine were dissolved into the starch syrup solution to obtain the same viscosity as the mixing fluid. Concentrations of sodium thiosulfate solution and iodine solution were 0.5 mol/l. The iodine solution was added to the mixing fluid, and then the thiosulfate solution was added to the mixing fluid at the liquid surface. The ratio of the iodine solution and the thiosulfate solution was 1 to 1.4. This ratio was allowed to judge the mixing time easily [5]. So, added volume of the iodine solution and the thiosulfate solution were 1 ml and 2.8 ml, respectively. These experimental methods are the same as previous papers [6].

A 500 ml glass beaker was used for the small-scale experiment. A small-scale HB impeller made from a PTFE board was installed on a cylindrical stirring bar, as shown in Figure 2. The vessel diameter $D$, the impeller diameter $d$, and the impeller height $b$ are 0.085 m, 0.05 m, and 0.045 m, respectively. The attachment and removal of a normal
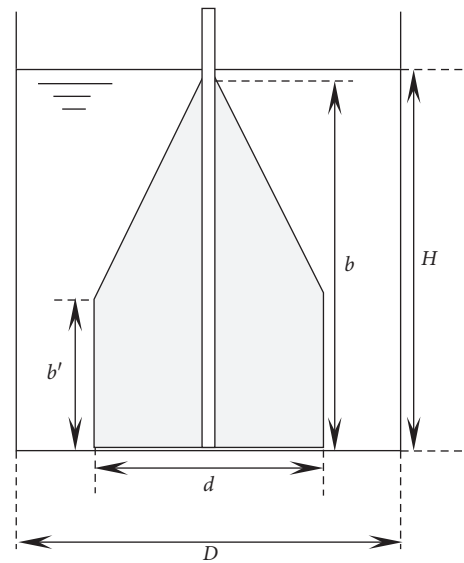


FIGURE 1: Schematic diagram of the HB-type impeller.



FIGURE 2: HB-type stirring bar.

cylindrical stirring bar of an HB impeller is very easy, because the stirring bar is simply forced into a hole in the lower part of the HB impeller.

## 3. Results and Discussion

*3.1. Mixing Performance of the HB Impeller for the Pilot Scale.* First, Figures 3 and 4 show typical streak line patterns of a two-blade paddle impeller. Although the streak line pattern was different at different Reynolds numbers, the same pattern was observed at the same Reynolds number, even if the impeller rotational speed and the vessel size were changed. A pair of isolated mixing regions (IMRs) were observed in the laminar flow region at Re = 10 and 70.

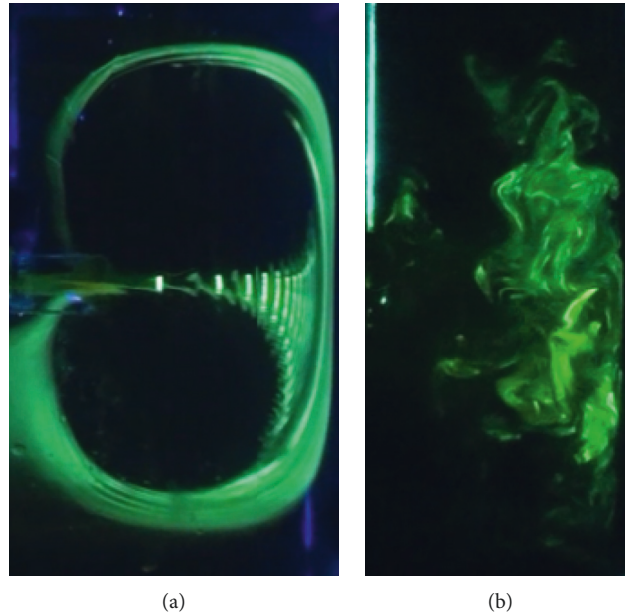Figure 5 shows a time series of the typical streak line patterns of the HB impeller. The streak line pattern spreads

(a)             (b)

FIGURE 3: Streak line patterns of a paddle impeller at Re = 10 (a) and Re = 2,600 (b).
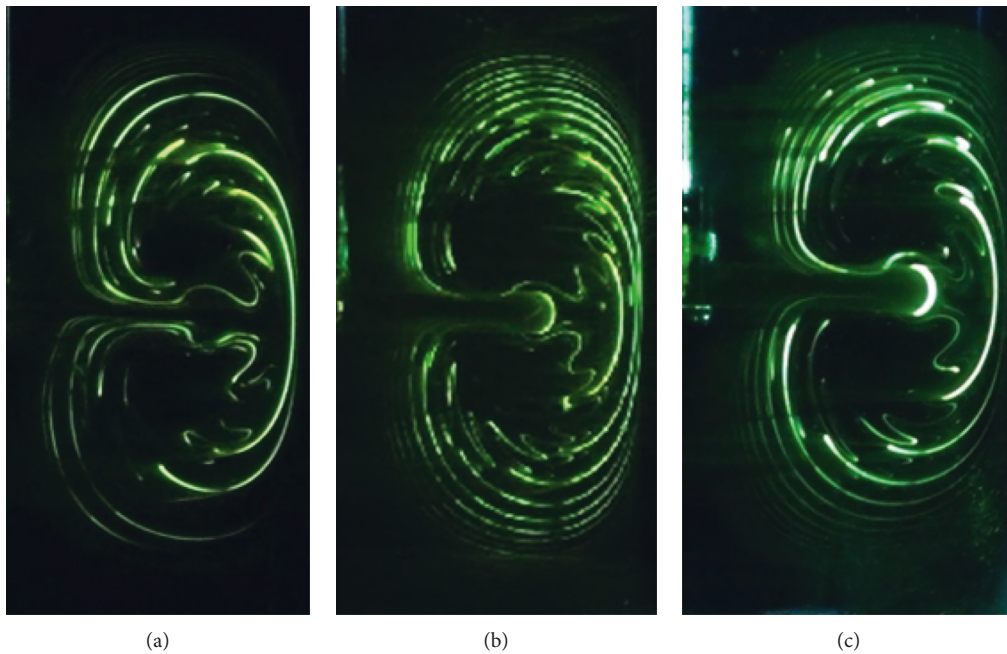


(a)         (b)         (c)

FIGURE 4: Streak line patterns of a paddle impeller at Re = 70. (a) $n$ = 25 rpm; (b) $n$ = 50 rpm; (c) diameter = 1.3 $D$.

speedily throughout the vessel after a few rotations of the impeller, whereas no IMR was observed.

Figures 6 and 7 show time series of the mixing process of the HB impeller. An IMR shaped like a doughnut was not observed in the laminar region, and no cylindrical rotation zone (CRZ) was observed in the turbulent region in vessels with either a flat or dished bottom. The most important consideration in the operation of the HB impeller is that the installment of baffles is not necessary under a wide range of Reynolds numbers. The optimum ratio of the impeller diameter to the vessel diameter ($d/D$) was found to be 0.6 to 0.7. This ratio is the same as that of the other two-blade wide paddle impellers considered herein. The power number of the HB impeller was estimated (1) in the laminar region, in which the correlation of MB, FZ, and MR205 can be used and (2) in the turbulent region, in which the correlation of the paddle impeller can be used when impeller height is considered to be $b'$ (see Figure 1) [7].

*3.2. Mixing Performance of the HB Impeller for the Laboratory Scale.* Figures 8 and 9 show mixing processes using a normal magnetic cylindrical stirring bar and the HB impeller in
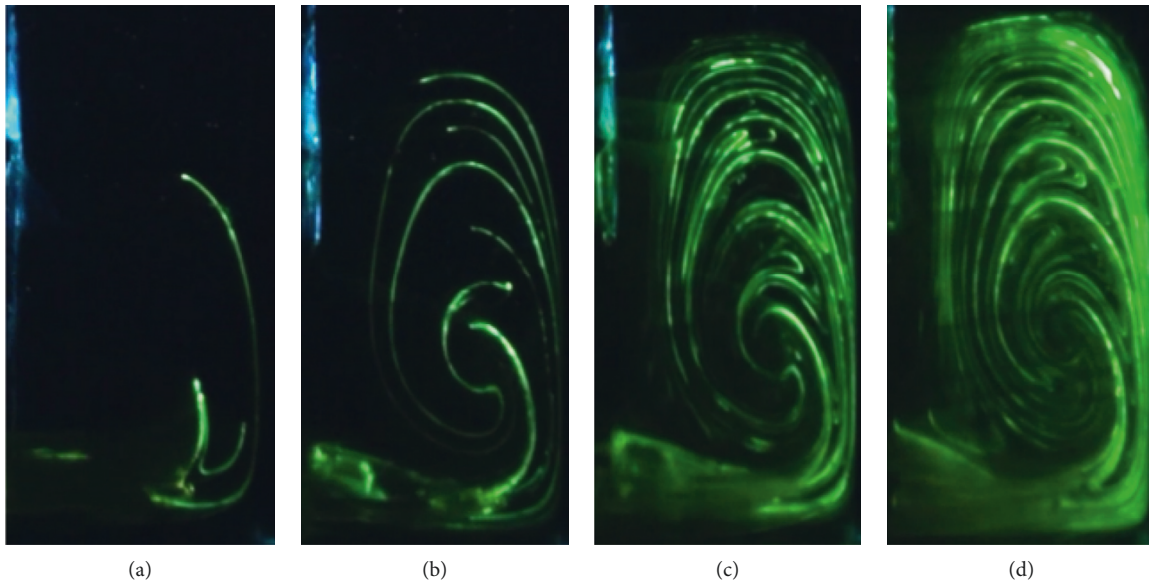
(a)　　　　　　　　(b)　　　　　　　　(c)　　　　　　　　(d)

FIGURE 5: Streak lines generated by the HB-type impeller. (a) Rotation = 4; (b) rotation = 6; (c) rotation = 10; (d) rotation = 14.



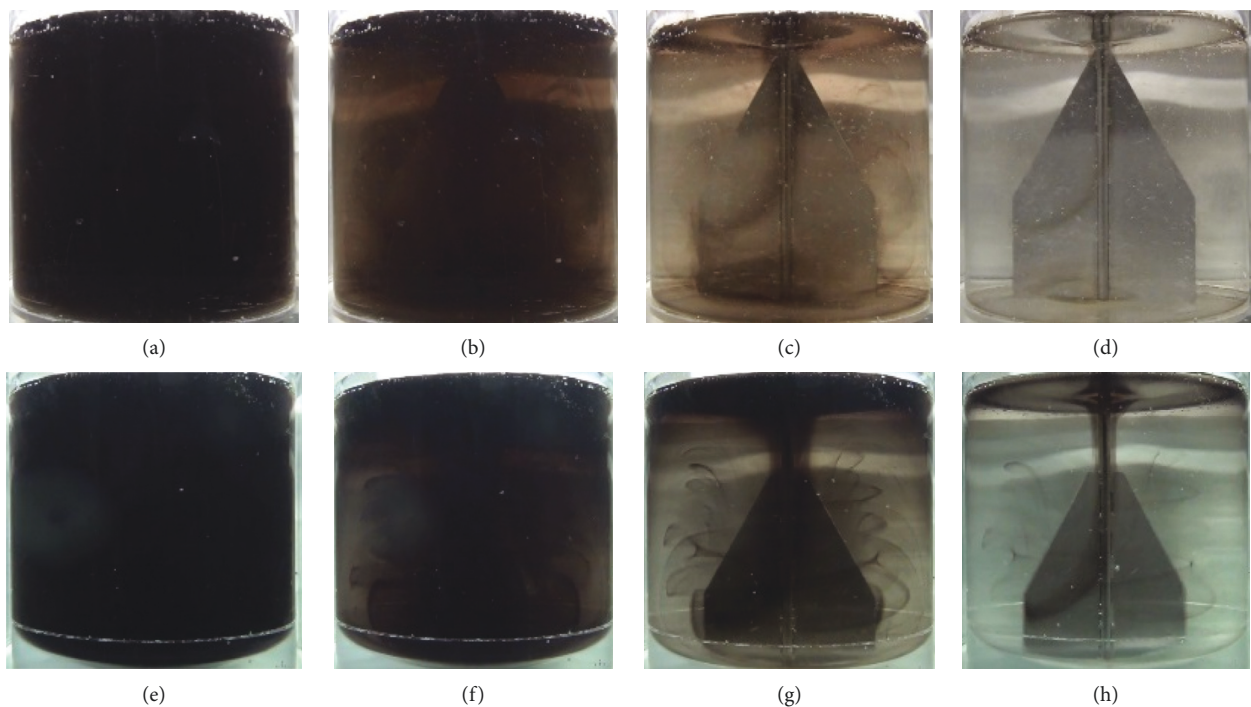(a)　　　　　　　　(b)　　　　　　　　(c)　　　　　　　　(d)

(e)　　　　　　　　(f)　　　　　　　　(g)　　　　　　　　(h)

FIGURE 6: Mixing process of HB impeller at Re = 100, flat bottom ((a) 0 s, (b) 10 s, (c) 15 s, and (d) 30 s) and dished bottom ((e) 0 s, (f) 10 s, (g) 15 s, and (h) 30 s) ($\mu$ = 0.29 Pa·s, $\rho$ = 1,327 kg/m$^3$, and $n$ = 100 rpm).

a 500 ml beaker, respectively. The fluid viscosity was 60 mPa·s in the cylindrical stirred bar, whereas the HB-type stirring bar (Asahi Glassplant Inc.) achieved complete mixing in the beaker, as shown in Figure 9. Figures 10 and 11 show the mixing processes of the normal cylindrical stirring bar and the HB impeller in a 500 ml beaker filled with deionized water in the turbulent region. A CRZ was observed in the vessel stirred with a normal bar, as shown in Figure 10. However, the CRZ was not observed in the vessel mixied with HB-type bar, and complete mixing was achieved quickly at a lower rotational speed. It was difficult to measure the power consumption of the HB impeller for the laboratory scale because it was used with magnetic stirrer. However, the power consumption was able to be estimated by the correlation of the HB impeller [7].
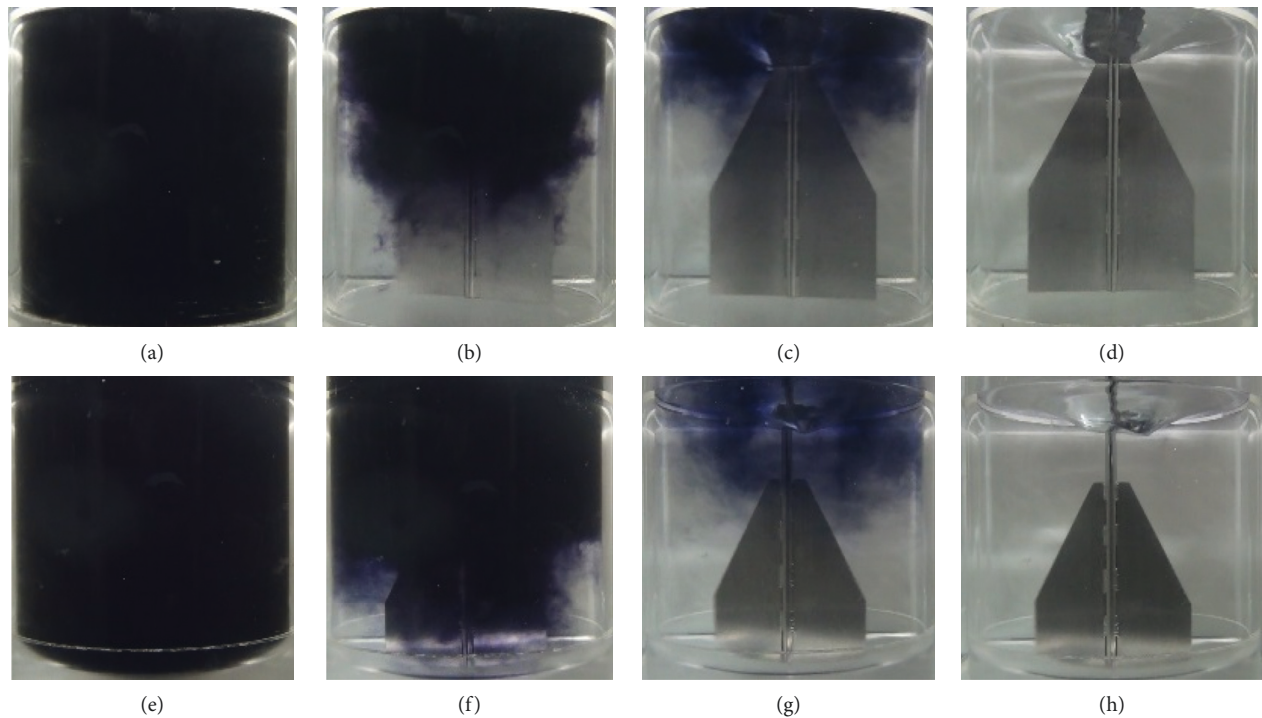
Figure 7: Mixing process at Re = 23,000 of HB impellers with a flat bottom ((a) 0 s, (b) 5 s, (c) 8 s, and (d) 10 s) and a dished bottom ((e) 0 s, (f) 5 s, (g) 10 s, and (h) 12 s) ($\mu = 1$ mPa·s, $\rho = 1,000$ kg/m$^3$, and $n = 100$ rpm).
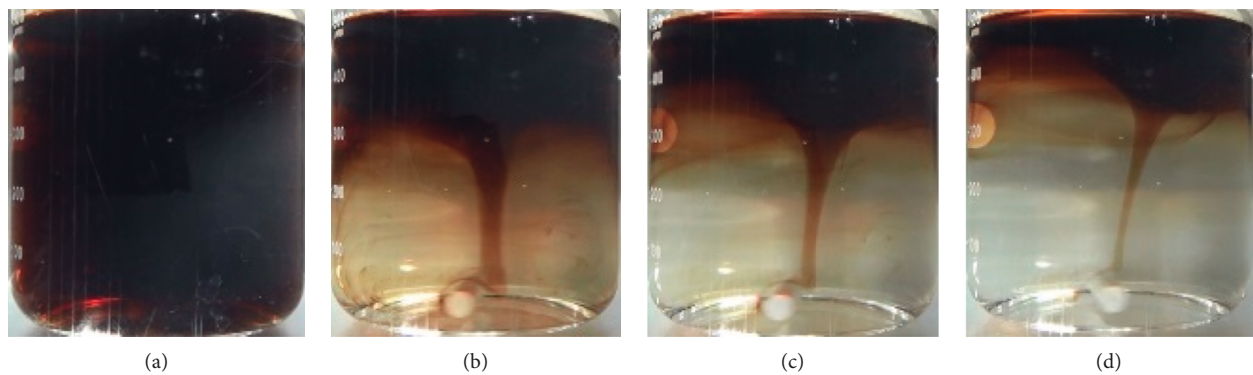


Figure 8: Mixing using a normal bar at $n = 100$ rpm. (a) 0 s, (b) 60 s, (c) 120 s, and (d) 300 s.
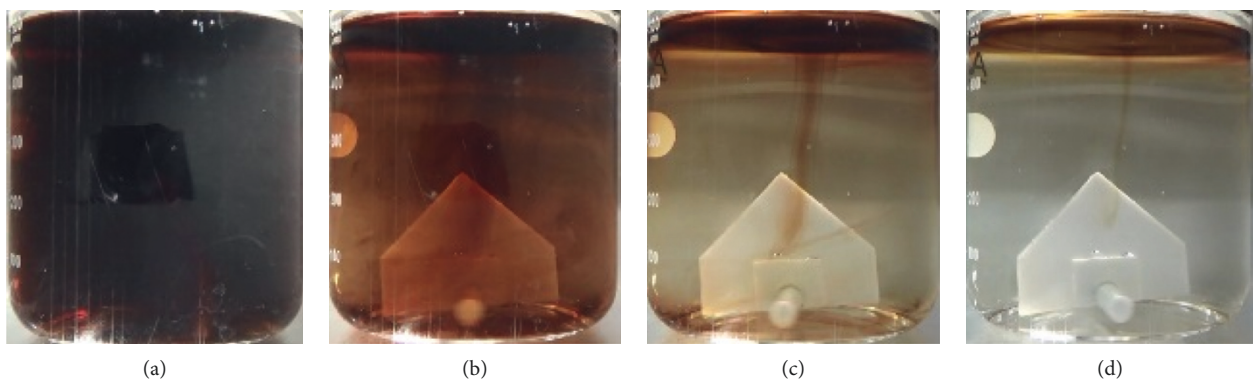


Figure 9: Mixing using an HB-type bar at $n = 100$ rpm (Re = 80). (a) 0 s, (b) 10 s, (c) 20 s, and (d) 60 s.
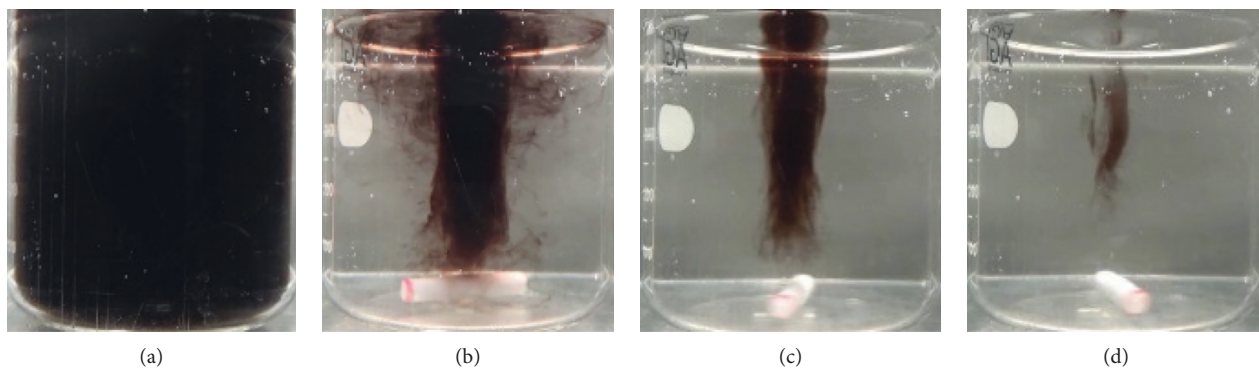
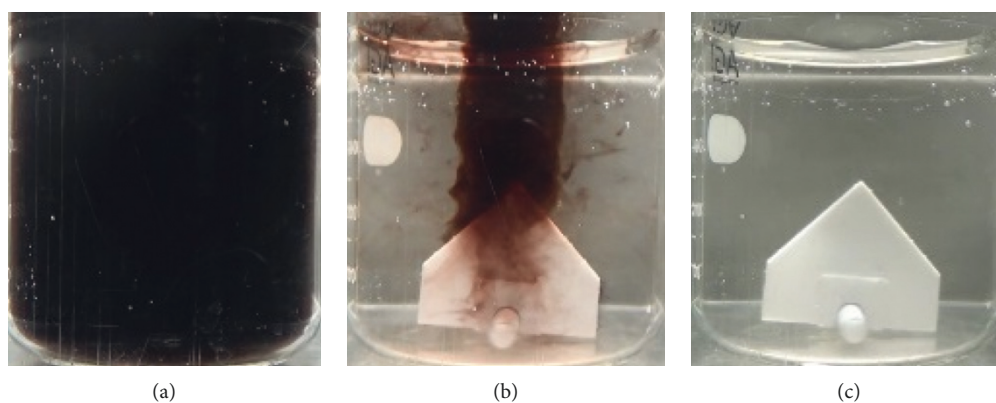FIGURE 10: Mixing using a normal bar at $n$ = 200 rpm. (a) 0 s, (b) 5 s, (c) 20 s, and (d) 40 s.



FIGURE 11: Mixing using an HB-type bar at $n$ = 100 rpm (Re = 4,200). (a) 0 s, (b) 5 s, and (c) 13 s.
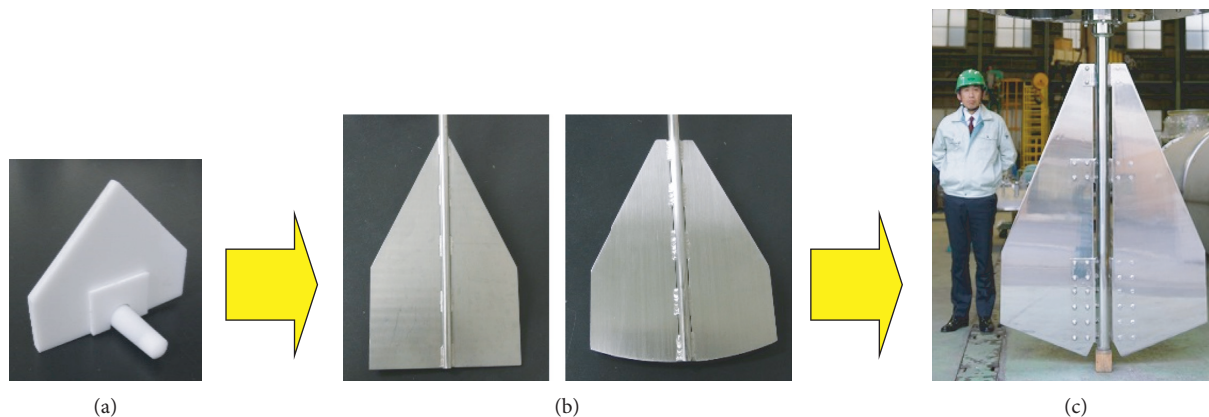


FIGURE 12: Scale-up system of the HB impeller. (a) Laboratory scale (500 mL), (b) pilot scale (5 L), and (c) Industrial scale (4 m$^3$).

As described above, the HB-type impeller can be used in a small-scale vessel. On the other hand, other two-blade wide paddle impellers developed by Japanese companies cannot be used because their geometrical shape is very complicated. In addition, the geometrical shapes of these other impellers are complicated, which makes them difficult to wash, and they are not suitable for laboratory use.

Generally, in organic synthesis, polymerization, inorganic reactions, and dispersion of a catalyst, a normal cylindrical stirring bar is used. However, the proposed HB

impeller will improve the efficiency of such synthetic reactions in the laminar region. As shown in Figure 8, complete mixing cannot be achieved using the normal.

3.3. Scale-Up of the HB Impeller to Industrial Scale. An industrial-scale HB impeller ($D$ = 1.7 m) has been developed by Takasago Chemical Engineering Co. Ltd. based on the above-described considerations, as shown in Figure 12.

## 4. Conclusions

Scale-up of the novel HB-type impeller became very easy because the geometrical shape of the impeller can be kept consistent from an experiment at laboratory scale to production at an industrial scale. In addition, since geometrical similarity is to be maintained, the proposed HB-type impeller addresses one of the difficulties in scale-up to industrial-scale production.

## Nomenclature

$b$: Height of the impeller blade (m)
$b'$: Height of the discharge part of the impeller blade (m)
$D$: Vessel diameter (m)
$d$: Impeller diameter (m)
$H$: Liquid depth (m)
$n$: Impeller rotational speed ($s^{-1}$)
$Re$: Impeller Reynolds number ($= nd^2\rho/\mu$) ( - )
$\mu$: Liquid viscosity (Pa·s)
$\rho$: Liquid density (kg·m$^{-3}$)

## Data Availability

The experimental data used to support the findings of this study are included within the article.
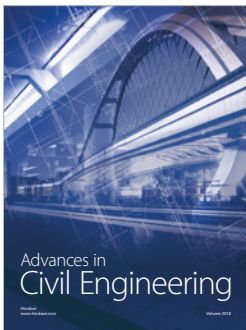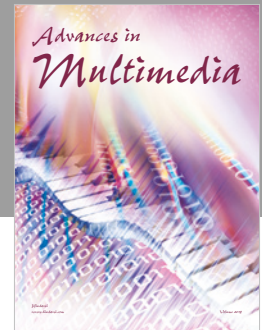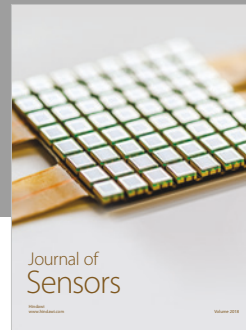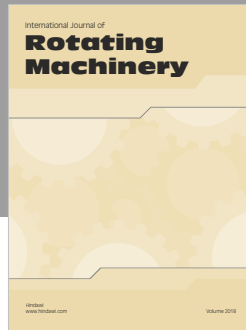
## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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