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Article

Effect of Baffle Clearance on Scale Deposition in an Agitated Vessel

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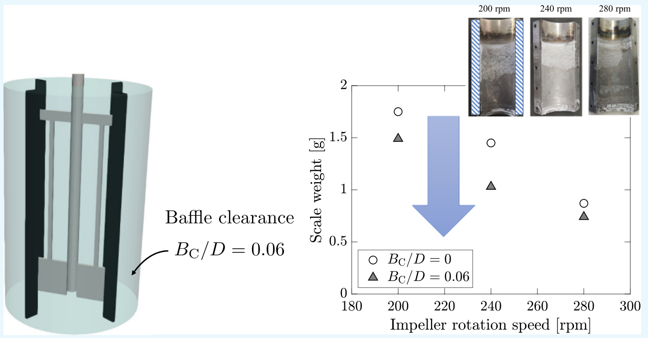
ABSTRACT: The material deposition in a mixing tank agitated by the MAXBLEND impeller in a turbulent state was quantified and compared between cases with and without baffle clearance. Magnesium hydroxide formed from the chemical reaction between calcium hydroxide and magnesium chloride was used as a model of scale formation. Flow velocity in the tank was investigated by employing computational fluid dynamics simulation and experimentally validated by an ultrasonic velocity profiler method. Results showed that the amount of scale decreased with the increase in the rotational speed of the impeller due to the erosion effect on the tank wall. In the case without baffle clearance, the smaller weight of the scale was deposited on the front of the baffle plate due to the flow impingement, which enhanced the removal of the scale deposition. However, the lower-velocity magnitude behind the baffles resulted in an enhancement in the formation of scale. Installation of baffle clearance caused a contraction flow in between the tank wall and baffles, and consequently, the higher flow velocity reduced the amount and thickness of the scale. Measurement of the torque showed that the baffle clearance did not affect the power consumption, so the installation of baffle clearance can be a promising approach to reduce scale deposition in terms of saving operational costs and increasing process efficiency and safety.



■ INTRODUCTION

Agitated vessels have been widely used not only in chemical industries but also in food or mining industries to accomplish mixing, chemical reactions, or dispersion. The flow pattern in the vessel induced by the rotating impeller strongly affects mixing performances.[1] This has led to the development of various kinds of impellers so far. Characteristics of these impellers including power consumption and mixing time have been investigated by many researchers.[2−4] The selection of tank geometry and the number of baffles also have a significant impact on the performance of a process.

Most conventional mixing vessels have baffles attached to their side wall in a turbulent flow to avoid the circumferential flow being dominant and the vertical circulation flow becoming weaker. Installation of baffles breaks the vortex, which appears in the case without baffles and further improves the mixing performance since the rotating flow impinges on the baffles.[5] Baffles are often designed by the standard baffle condition; however, in some cases, a lower mixing efficiency can be obtained, which is not worth the power consumption.[6] The effect of baffles on power consumption has therefore been investigated for a long time.[7−9]

Scale, a hard deposit attached to the tank wall, has been a significant issue in many industries such as mining industries. Scale increases cleaning costs, reduces production capacity, and hazards the health of operators, which consequently leads to a significant economic loss in the process. A commonly used strategy to prevent scaling is adding chemical antiscalants, suppressing the growth of a scale layer and promoting the dissolution of the deposition. The literature provides a kinetic model for the scale inhibition mechanism;[10] however, industrial application of antiscalants is strongly based on empiricism. This is because the efficiency of antiscalants relies on the type of the chemical reaction. It is, therefore, necessary to design a reactor for preventing scale deposition rather than use chemical antiscalants.

One of other approaches to overcome the scale issue is to control the flow velocity. Hoang (2015),[11] Walker and Sheikholeslami (2003),[12] and many other researchers had investigated the hydrodynamic effects on scale formation and showed that the velocity in the reactor had an important role in the suppression of scale growth. In the fully developed turbulent-flow regime, Ceylan and Kelbaliyev (2003) showed

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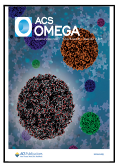

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that an increase in flow velocity was capable of decreasing the scale thickness in pipes.[13] Nawrath et al. (2006) experimentally examined the scale growth in alumina refineries and suggested that a slurry flow velocity of more than 2.9 m/s near the walls of the tank could reduce the rate of scale growth to zero on the tank walls.[14] Wu et al. (2012) applied a swirl flow agitator to a mineral process and showed that the growth of scale can be reduced compared to that in a conventional draft tube agitator system.[15] Davoody et al. (2019) conducted a qualitative and quantitative investigation on the scale deposition on the wall of an agitated tank and showed that the scale thickness was lower in the unbaffled tank than that in the baffled tank.[16] This reduction of the scale thickness in the unbaffled tank resulted from no stagnant region behind a baffle where the tangential velocity was very slow.

The present paper experimentally investigated the effect of clearance between baffles and the tank wall on the scale deposition to overcome the scale formation behind baffles. The agitation was provided by a MAXBLEND impeller,[17] a large impeller developed by Sumitomo Heavy Industries in Japan. An experimental method presented by Davoody et al. (2017) was used as a model of scale deposition, which utilized the production reaction of magnesium hydroxide [$Mg(OH)_2$]. The amount of scale and its distribution on the side wall were discussed with the flow velocity in the tank obtained by numerical simulation.

RESULTS AND DISCUSSION

Velocity Validation of Computational Fluid Dynamics Results by the Ultrasonic Velocity Profiler. The numerical results were validated by experimental results in terms of the axial velocity distribution. Time-averaged axial velocity during 100 s was obtained from the time-series velocity data from the ultrasonic velocity profiler (UVP) measurement. Numerical results of the velocity were also averaged in time. Figure 1 shows the vertical profiles of the axial velocity component along the line defined by r/R = 0.9 and θ = 45° in the cylindrical coordinate system. As depicted in Figure 2, relatively good agreement of the velocity distribution can be seen between experimental and numerical results. Only some small discrepancies existed in the simulation and experiment; however, two local maxima were observed, and the values at the two maxima were very similar. It indicated that the simulation model was reliable, and the validity of the numerical procedure was confirmed.

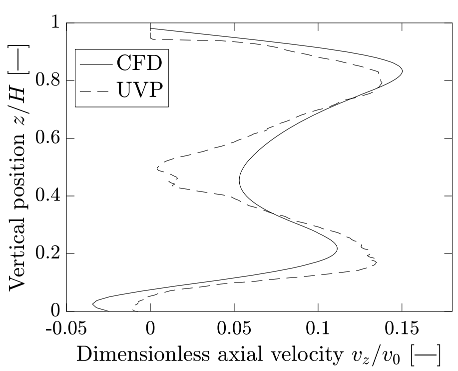

Figure 1. Comparison of the dimensionless axial velocity profile in the vertical direction between numerical and experimental results.

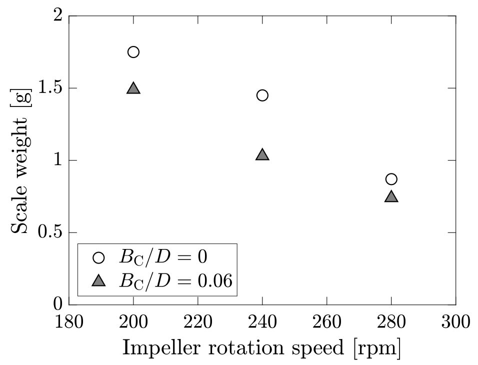

Figure 2. Effects of impeller rotation speed and baffle clearance on the weight of the formed scale.

Effect of the Impeller Rotation Speed on Scale Weight. Figure 2 describes the effects of the rotational speed of the impeller and baffle clearance on scale weight. The weight of scale decreased with the impeller rotation speed regardless of the configuration of baffle clearance. This tendency is consistent with the case of a small agitator using the Lightnin A310[18] and can also be seen in the case of the pipe flow.[14] As Wu et al.[15] pointed out, the removal of the material deposit can occur simultaneously with the formation of scale. In this complex process, this result, therefore, shows that the speed of the removal of the material deposit was much more accelerated than that of the scale growth.

Effect of Baffle Clearance on Scale Deposition. Figures 3 and 4 illustrate the distribution of the formed scale on the tank wall with and without baffle clearance (B_C/D = 0 and 0.06), respectively. In the photographs for the case without baffle clearance (Figure 3), baffles were attached to both sides of the disassembled tank walls, which are illustrated as striped boxes. On the other hand, for the case with baffle clearance (Figure 4), baffles were placed on the center. In all the photographs, the fluid flowed from the left to the right. In the case without baffle clearance, the smaller weight of the scale was deposited on the tank wall in front of the baffles, while the

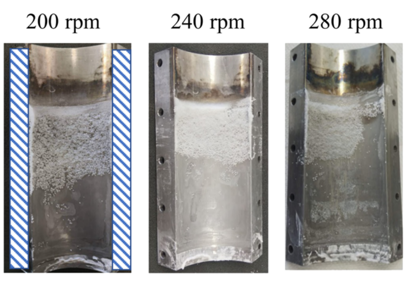

Figure 3. Distribution of scale deposition for B_C/D = 0.

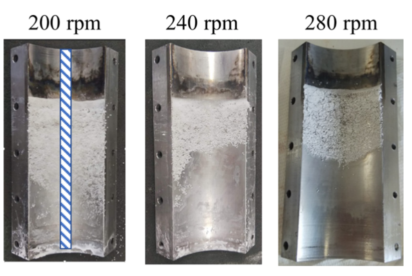

Figure 4. Distribution of scale deposition for B_C/D = 0.06.

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weight of the scale was larger behind the baffles. A decrease in the scale thickness and area of the wall covered by the scale was observed for $B_C/D = 0.06$, which resulted in the decrease in the weight of scale by the installation of baffle clearance, as described in Figure 2. Moreover, the suppression of deposition behind baffles was significantly improved in the case with baffle clearance.

Figure 5 shows the numerically obtained tangential velocity between a baffle and the side wall when the impeller position is at $\theta = 45°$. The baffle is placed at $\theta = 0°$, and the flow goes from the right to the left (counterclockwise) in Figure 5. When $B_C/D = 0$, the flow impinged on the baffles, which resulted in a decrease in the tangential velocity in front of a baffle and behind a baffle. This flow impingement caused the erosion of the scale in front of baffles, and a decrease in the tangential velocity behind baffles promoted scale growth, which can be observed in Figure 3. In the case with baffle clearance (B_C/D = 0.06), the velocity decrease around baffles completely disappeared, and a significant increase in the flow velocity near the side wall can be seen. Because of the occurrence of the contraction flow, the tangential velocity drastically increased through the gap between the baffles and side wall. Consequently, this higher flow velocity eroded deposits, which resulted in a decrease in scale weight, as can be seen in Figure 2.

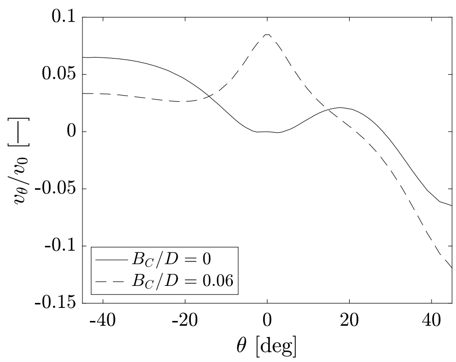

Figure 5. Tangential velocity profile in the azimuthal direction at r/R = 0.92 and z/H = 0.5 for N = 240 rpm.

Most processes using agitated tanks are designed based on the power diagram of the impeller since the main equipment such as a motor must have a sufficient impact on the power consumption. The power consumption has direct effects on the economy of the process. Figure 6 shows the relationship between the rotational speed of the impeller and the power consumption by the correlation between the Reynolds number Re ($= \rho N d^2/\mu$) and the power number N_p ($= P/\rho N^3 d^5$). The tested impeller rotational speed in the scale experiment N = 200−280 rpm corresponds to Re in the range of $1.3{-}1.8 \times 10^4$. It was found that in the turbulent region, installation of baffle clearance slightly saved the power consumption; however, it did not have a significant impact on the reduction in energy. Considering the decrease in the scale deposition shown in Figure 2, installation of baffle clearance can reduce the scale under the same energy consumption without adding chemical antiscalants and can be a promising approach to increase the process efficiency from the viewpoint of operational costs and process safety.

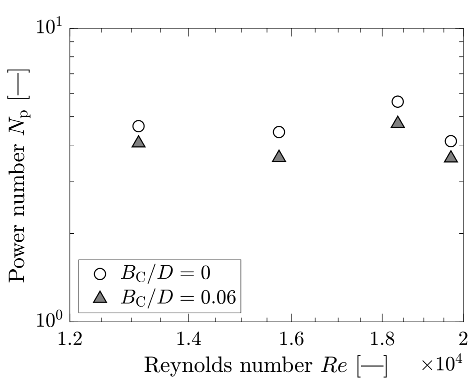

Figure 6. Relationship between N_p and Re

CONCLUSIONS

The effects of clearance between baffles and the tank wall on the material deposition were investigated in a turbulent-flow regime using a large impeller, the MAXBLEND impeller. Scale growth was reduced as the rotational speed of the impeller increased both in the case with and without baffle clearance. In the case without baffle clearance, a smaller weight of scale was obtained due to the flow impingement on baffles, which enhanced the removal of the scale deposition. However, the lower-velocity magnitude behind the baffles resulted in the formation of scale in a larger amount. Installation of baffle clearance caused a contraction flow in between the tank wall and baffles, and consequently, the higher flow velocity reduced the scale deposition there. It was shown that the installation of baffle clearance did not reduce the energy consumption; however, from the viewpoint of operation cost and process safety, it can be a promising approach to improve the process efficiency.

EXPERIMENTAL SECTION

Quantification of Scale Formation. The disassemblable tank made of stainless steel was used for scale quantification experiments. Agitation was provided by the MAXBLEND impeller, which was set to the vertical axis of the tank and driven by a motor, as shown in Figure 7. Two baffle arrangements were tested, that is, the case with the clearance between the baffles (B_C/D = 0.06) and tank wall and the one without clearance (B_C/D = 0). Geometric details of the tank, impeller, and baffles are given in Table 1.

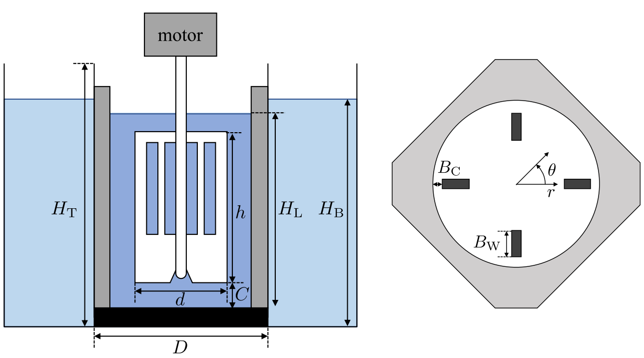

Figure 7. Schematic of the experimental setup (left) and top view of the tank with clearance (right).

The scale used in this study is magnesium hydroxide [$Mg(OH)_2$], formed from the chemical reaction between

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Table 1. Tank, Impeller, and Baffle Dimensions

symbol	parameter	value
D	tank diameter	100 mm
H_T	tank height	200 mm
H_L	liquid height	160 mm
H_B	water bath height	220 mm
d	impeller diameter	62.8 mm
h	impeller height	139 mm
C	impeller clearance from the tank bottom	10 mm
B_L/H_L	dimensionless baffle height	1.0
B_W/D	dimensionless baffle width	0.1
B_C/D	dimensionless baffle clearance	0 or 0.06
—	the number of baffles	4

calcium hydroxide [$Ca(OH)_2$] and magnesium chloride ($MgCl_2$). 500 mL of $Ca(OH)_2$ solution with a concentration of 0.6 M and 500 mL of 0.5 M sodium carbonate (Na_2CO_3) solution were prepared as the initial liquid and fed into the tank. The tank filled with the initial liquid was placed into a thermostatic bath, which was kept at 80 °C. After the liquid temperature reached a steady state, 15 g of $MgCl_2$ powder was gradually added into the tank with agitation. The duration of the experimental run was 45 min to sufficiently precipitate magnesium hydroxide on the tank wall. The solution in the tank was then withdrawn at a rate of 61.76 mL/s. After pumping out, the weight of the formed scale was measured as the difference in the weights of the tank before and after the experiment. The impeller rotating speed was varied from 200 to 280 rpm. A more detailed experimental methodology can be referred in the paper of Davoody et al. (2017).[18]

Flow Velocity and Power Consumption Measurement. Flow velocity in the agitated tank was measured by a UVP for the validation of the numerical results. The UVP is a powerful tool to directly obtain the flow field along the ultrasonic beam axis and is now used not only in the pipe or duct flow[19,20] but also in the flow in complex geometries.[21] An ultrasonic pulse wave irradiates the fluid containing tracer particles, and the Doppler shift frequency of the echoed ultrasound is then detected as a function of time. Flow velocity is calculated based on the proportional relationship with the Doppler shift frequency. The detailed principle of UVP measurement can be seen in the literature study of Takeda (2012).[22]

A commercial UVP device (UVP-DUO, Met-Flow SA) and co-polyamide particles were used. The particle size was 80–200 μm in diameter, and the density was 1070 kg/m^3. The ultrasonic pulse was emitted from the transducer at a pulse repetition frequency of 1.87 kHz. The diameter of the sensor was 8 mm, and the basic frequency was 4 MHz. The geometrical configurations of the impeller and acrylic-made tank for UVP measurement were the same as those shown in Figure 7.

The power consumption of the impeller was measured with a torque meter (i-stirrer ls600, Trinity-Lab Inc.). The power consumption P was calculated by eq 1 using the rotational speed of the impeller and average torque T measured for at least 180 s in each run.

$$P = 2\pi NT \tag{1}$$

The tank, impeller, and baffle were the same as those used in UVP measurement. All measurements were done at room temperature.

COMPUTATIONAL FLUID DYNAMICS MODEL

The flow velocity and flow pattern were numerically obtained by computational fluid dynamics software RFLOW (Rflow Co., Ltd.). The fluid was considered as an incompressible Newtonian fluid, and its properties were set to be the same as those of water. The conservation and Navier–Stokes equations were solved. The SIMPLE algorithm was applied to couple pressure and velocity. The standard $k-\varepsilon$ model[23] was used in this simulation due to stability and computational cost. As for the boundary conditions, the top liquid surface of the tank was set as a slip wall, and the other tank walls and the impeller surface were set as nonslip walls. The mesh number was 40 × 120 × 80 in the radial, azimuthal, and axial directions, respectively. The total number of numerical cells was more than 3.8×10^5.

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE

B_C clearance between the tank wall and baffles [m]
B_L length of the baffle [m]
B_W width of the baffle [m]
C clearance between the tank bottom and the impeller [m]
d diameter of the impeller [m]
D diameter of the tank [m]
h height of the impeller [m]
H_B height of the water bath [m]
H_L height of the liquid [m]

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H_T height of the tank [m]
N impeller rotational speed [s^{-1}]
N_p power number [—]
P power consumption [W]
r radial coordinate [m]
R radius of the tank [m]
Re Reynolds number [—]
T torque in time series [N m]
v velocity [m/s]
v_0 impeller tip velocity [m/s]
z axial coordinate [m]
θ azimuthal coordinate [°]
μ viscosity [Pa s]
ρ density [kg/m^3]

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