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Research Article
Numerical Study of Power Characteristics for Stirring Device of Sand Blender

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Abstract
Acting as one of the core devices of sand blender, the stirring effect of sand blender stirring device had an important effect on the quality of the fracturing fluid and the effect of fracturing operation. It was necessary to study the power characteristics of the sand blender stirring device that because the power characteristics of the sand blender stirring device were closely related to the stirring effect. In this study, the CFD model of the sand blender stirring system was established by using the Computer Aided Design (CAD) and Computational Fluid Dynamics (CFD) software, the influence of the baffle number, the spacing of dual mixing impeller, the upper mixing impeller diameter and the lower mixing impeller diameter on the stirring power were analyzed based on this. The results shown that the baffle number and the spacing of the dual mixing impeller had less influence on the stirring power of the sand blender stirring device, but the upper and lower mixing impeller diameter had great influence on the stirring power of the sand blender stirring device. On the basis of the numerical simulation, the weight coefficients of the upper and lower impeller diameter and the equation of the stirring power were obtained by using the SPSS software to carry out nonlinear regression analysis. The NP-Recurve was obtained, according to the numerical simulation of different impeller rotational speed. The study results would provide reliable theoretical support for the calculation of the stirring power of the sand blender stirring device.

Key words: Sand blender, stirring device, power characteristics, power number, numerical simulation

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Fracturing sand blender is the main corollary equipment for oil field fracturing and sand control. It is mainly used for mixing, stirring, conveying the mixed media of the fracturing operation (Wu *et al*., 2013). Acting as one of the core devices of sand blender, the stirring effect of stirring device have an important effect on the quality of the fracturing fluid and the effect of fracturing operation (Zhou *et al*., 2014). With the development of the fracturing technology in recent years, multiple fracturing, massive fracturing and high sand-fluid ratio fracturing are widely used, the requirement of the fracturing equipment performance are power (Wu, 2008). The stirring device have the characteristics of uniform mixing, high stirring efficiency, large capacity, even displacement, easy control, to meet the needs of the high sand ratio, high precision, large capacity of the fracturing sand blender. It is necessary to study the power characteristics of the stirring device that because which have a close relationship with the stirring effect, it is a measurement of the stirring strength and move motion of the mixture in stirring device and it is the basis for determining the type and power of the motor (Wang and Feng, 2000).

At present, there is few similar article or relevant study about power characteristics for stirring device of the sand blender, but the research of the power of the other types of stirring device can be used for reference to the stirring device of sand blender. There are two research methods of stirring power; CFD numerical simulation and fluid test. The former one mainly adopts CFD software to study the power characteristics of stirring device (Chen *et al*., 2012; Zhong *et al*., 2003; Feng *et al*., 2011; Taghavi *et al*., 2011; Ameur *et al*., 2011) while the later one study the power characteristics of stirring device by fluid test device (Zhao *et al*., 2009; Yu *et al*., 2009; Bao *et al*., 2015; Scargiali *et al*., 2013; Abbott *et al*., 2014; Ghotli *et al*., 2013). The CFD numerical simulation has many advantages, comparing with fluid test, such as experimental equipment, size of experiment, cost of experiment, experiment period and so on, it has already widely used in many fluid machinery (Wang, 2004). This study which mainly focus on the power influence factors of dual mixing impeller of oil fracturing sand blender, including the number of baffle, the spacing of dual mixing impeller, the diameter of two impellers. The N_P-Recurve and stirring power theoretical formula is presented in this paper. It provides a reference for the stirring power calculation of the fracturing sand blender.

MATERIALS AND METHODS

Hydrodynamic model of the stirring device: The mixture is solid-liquid suspension, because it is mixed with water, additives and solid particles in blending tank of sand blender. According to the characteristics of the mixture, the simulation process is based on the following assumptions: (1) The solid particles and fluid coexist in blending tank, they are continuous medium, interinfiltration and have their own different speed and volume fraction. (2) The liquid phase is incompressible Newton fluid, the solid particles are composed of the same size and it is incompressible. (3) There is no mass transfer between solid particles and fluid phase, the interaction of solid particles and fluid phase is only drag force, ignore pressure gradient force, virtual mass force and Magus force. (4) Turbulence is isotropic, the influence of Brown diffusion on the solid particles can be neglected in comparison with the large Reynolds number turbulent diffusion.

The multiple frame of reference method is adopted for the CFD simulation of the stirring device, the research system is constant system, the law of fluid flow in stirred tank obeys the following law of conservation of mass and momentum.

Assume u is the velocity vector of fluid particle, x is the space coordinate, F is the external force. The mass conservation equation is as follows:

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

where, u_i is the component of the velocity vector, x_i is the component of the space coordinate, i = 1,2,3.

The momentum conservation equation is as follows:

$$\frac{\partial(\rho u_i u_j)}{\partial x_i}=\frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial u_i}\right)\right]-\frac{\partial p}{\partial x_j}+F_j+\frac{\partial\left(-\rho\overline{u'_i u'_j}\right)}{\partial x_i} \tag{2}$$

where, ρ is fluid density, u_j is the component of the velocity vector, x_j is the component of the space coordinate, j = 1,2,3, μ is fluid viscosity, p is pressure, F_j is the component of the external force.

The Reynolds stress tensor is added to the momentum conservation equation, which can be calculated by the RNG k-e turbulent model according to the stirring process, it is a complicated rotating flow. The Reynolds stress tensor equation is as follows:

$$\rho\frac{\partial k}{\partial t}=\frac{\partial}{\partial x_i}\left[\alpha_k\mu_{eff}\frac{\partial \varepsilon}{\partial x_i}\right]+G_k-\rho\varepsilon \quad (3)$$

$$\rho\frac{\partial \varepsilon}{\partial t}=\frac{\partial}{\partial x_i}\left[\alpha_k\mu_{eff}\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1\varepsilon}\frac{\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}-R \quad (4)$$

where, κ is turbulent kinetic energy, t is time, x_j is the component of the space coordinate, α_κ is turbulent Prandtl number, μ_{eff} is coefficient of virtual viscosity, G_κ is the turbulent kinetic energy production by laminar flow velocity gradient, ϵ is the turbulent kinetic energy dissipation, $C_{1\epsilon}$ and $C_{2\epsilon}\epsilon$ are empirical constant, R is the custom source term.

Geometric model: Taking the stirring device of 2500-type sand blender as the study subject. The stirred tank is composed of inner chamber and sandwich chamber, the water enter the into sandwich chamber through the tangential inlet and then enter into the inner chamber through the 12 upper and lower water inlet. The stirring device have dual mixing impeller, the upper mixing impeller is MIG type impeller, the lower mixing impeller is 45°C blade paddle, the geometry of the mixing impeller shown in Fig. 1. The stirred tank diameter is 1168 mm, the effective height of stirred tank is 780 mm, the baffle number is 4 (uniform distribution), the upper mixing impeller diameter is 750 mm, the lower mixing impeller diameter is 630 mm, the spacing of dual mixing impeller is 300 mm. The geometric model of stirring device was created by Pro/E software according to the structure characteristics of stirring device and the requirement of CFD analysis. The geometric model of stirring device was shown in Fig. 2.

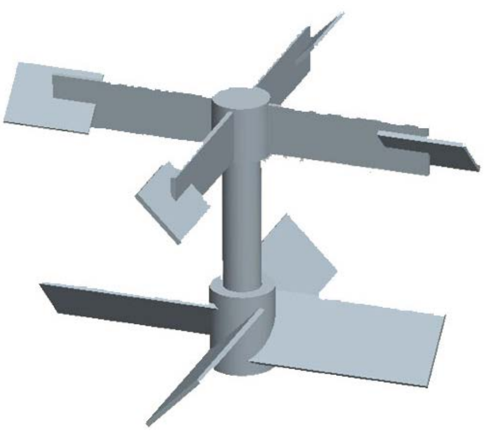

Fig. 1: Geometry of the mixing impeller

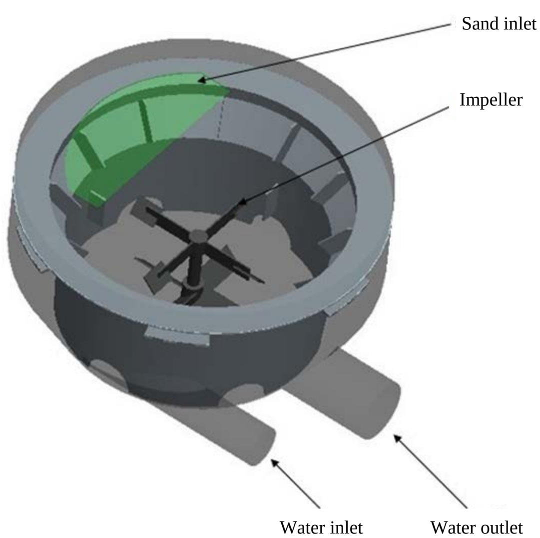

Fig. 2: Geometric model of the stirring device

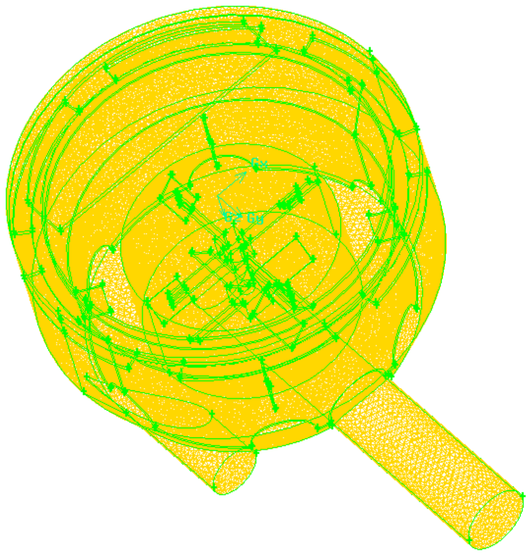

Fig. 3: Mesh of the stirring device

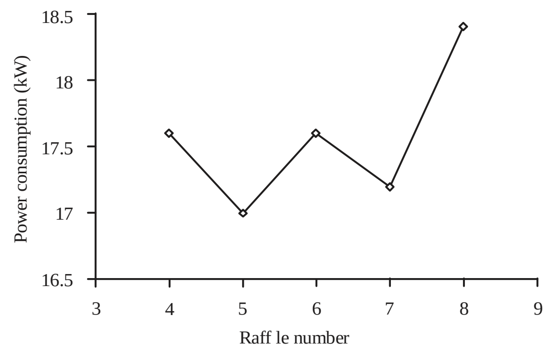

Fig. 4: The relationship between the baffle number and stirring power

Mesh generation: The geometric model of the stirring device was imported to the ANSYS Workbench software through the seamless interface between Pro/E and ANSYS Workbench, generated the mesh by using the pyramid mesh and the mesh of the region of the mixing impeller and the water inlet of the stirred tank was refined. The mesh of stirring device was shown in Fig. 3.

Boundary conditions: The rotating region was created around the mixing impeller and the interface was set between the stirred tank area and the rotating region. The boundary of the mixing impeller was set to moving wall, the water and sand inlet of the stirred tank was set to velocity inlet and the velocity of water and sand was calculated according to the ratio between sand and water. The gravitational acceleration was 9.81 m sec^{-2}, the rev of mixing impeller was 250 rpm.

RESULTS AND DISCUSSION

Influence of baffle number on the stirring power: The baffle is a rectangular plate which is fixed on the wall of the stirred tank. The function of the baffle is to control the liquid flow, strengthen the mixing effect of the suspension, but the baffle can affect the power consumption of the stirring system. At least four baffles were installed in stirred tank because the stirred tank diameter is bigger. In order to study the influence of the baffle number on the power consumption of stirring device, the numerical simulation was carried out when the baffle number was in range from 4-8 and the stirring power was obtained according to the analysis results. The relationship between the baffle number and stirring power was shown in Fig. 4.

As shown in Fig. 4, there was a small difference of stirring power when the baffle number was 4, 5, 6, 7 and 8. The maximum stirring power was 18.4 kW, when the baffle number was 8, the minimum stirring power was 17.0 kW, when the baffle number was 5, the difference between the maximum stirring power and the minimum stirring power was only 1.4 kW and the maximum difference rate of stirring power was 4.97%, compared with the baffle number was 4. The research result shown that the baffle number had little influence on the stirring power for the stirring device of sand blender and the 4 baffles had reached the full-baffle condition which was similar to the other analysis result (Liu and Tian, 2014), thus the result of numerical simulation was proved to be reliable.

Influence of the spacing of dual mixing impeller on the stirring power: The spacing of mixing impeller for the stirred tank with multi impellers has an effect on flow pattern, stirring power and mixing rate. In order to study this effect, the numerical simulation was carried out when the spacing of mixing impeller was 220, 240, 260, 280, 300, 320, 340, 360 and 380 mm, respectively, according to the structure characteristics of the stirring device and the height of the stirred tank and the stirring power was obtained according to the analysis results. The relationship between the spacing of the dual mixing impeller and stirring power was shown in Fig. 5.

As shown in Fig. 5, there was a small difference of stirring power when the spacing of the dual mixing impeller was between 220 and 380 mm. The maximum stirring power was 18.4 kW, when the spacing of the dual mixing impeller

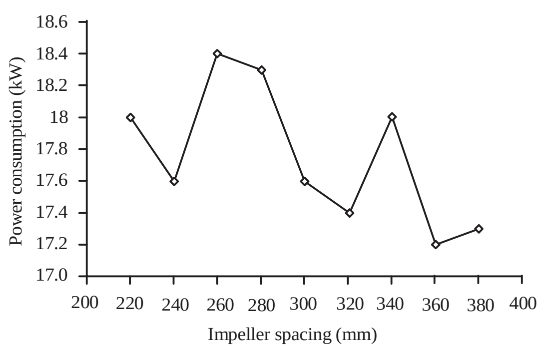

Fig. 5: The relationship between the spacing of the dual mixing impeller and stirring power

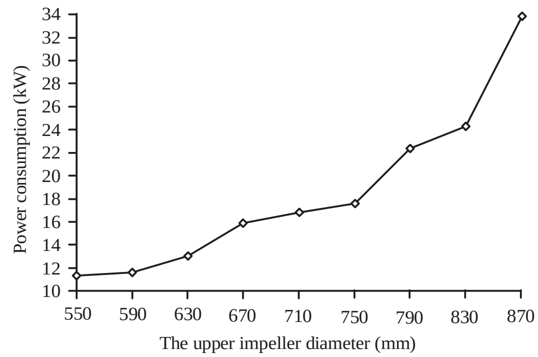

Fig. 6: The relationship between the upper mixing impeller diameter and stirring power

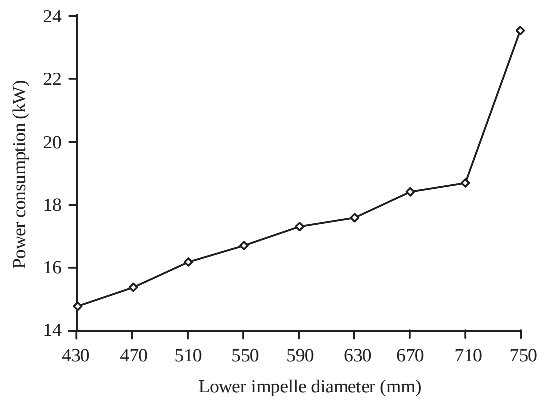

Fig. 7: The relationship between the lower mixing impeller diameter and stirring power

was 8, the minimum stirring power was 17.0 kW, when the spacing of the dual mixing impeller was 5, the difference between the maximum stirring power and the minimum stirring power was only 1.2 kW and the maximum difference rate of stirring power was 4.55%, compared with the spacing of the dual mixing impeller was 300 mm. This research result shown that the spacing of the dual mixing impeller had little influence on the stirring power for the stirring device of sand blender which was similar to the other research result (Wang, 2004), because the ratio of the spacing of the dual mixing impeller to the stirred tank diameter was in range from 0.19-0.33, which was limited by the height of the stirred tank.

Influence of the upper mixing impeller diameter on the stirring power: The mixing impeller diameter was one of the major factors in stirring power, the numerical simulation was carried out when the upper and lower mixing impeller diameter at different values and the influence rule of stirring power were obtained in this paper. The numerical simulation was carried out when the lower impeller diameter was fixed and the upper impeller diameter was 550, 590, 630, 670, 710, 750, 790, 830 and 870 mm, respectively, according to the structure characteristics of the stirring device and the stirred tank diameter and the stirring power was obtained according to the analysis results. The relationship between the upper mixing impeller diameter and stirring power was shown in Fig. 6.

As shown in Fig. 6, the change of the upper mixing impeller diameter had a significant impact on stirring power and the stirring power increased as the upper mixing impeller diameter increased, the result was consistent with the calculation equation of stirring power (Eq. 5).

Influence of the lower mixing impeller diameter on the stirring power: The numerical simulation was carried out when the upper impeller diameter was fixed and the lower impeller diameter was 430, 470, 510, 550, 590, 630, 670, 710 , and 750 mm, respectively, according to the structure characteristics of the stirring device and the stirred tank diameter and the stirring power was obtained according to the analysis results. The relationship between the upper mixing impeller diameter and stirring power was shown in Fig. 7.

As shown in Fig. 7, the change of the lower mixing impeller diameter had a significant impact on stirring power and the stirring power increased as the lower mixing impeller diameter increased, the result was consistent with the calculation equation of stirring power (Eq. 5).

Power number: The stirring power required depends on the desired flow pattern and turbulence, which is a function of the impeller structure and geometry size, impeller rotational speed, stirred tank structure and geometry size, impeller installation position and it can be calculated by the Eq. 5.

$$P = N_P \rho N^3 d^5 \quad (5)$$

where, P is power consumption, N_P is power number, ρ is fluid density, N is impeller rotational speed, d is impeller diameter.

When the power number was calculated, only the upper and lower impeller diameter were considered, because they had a great influence on the stirring power, the baffle number and the dual mixing impeller spacing were less affected, according to the analysis results. As the stirring device had dual mixing impellers and the upper and lower mixing impeller diameter was different, the impeller diameter d had to consider about the influence of the upper and lower mixing impeller in Eq. 5 and the stirring power can be calculated by the Eq. 6.

$$d = k_1 d_1 + k_2 d_2 \tag{6}$$

where, d_1 is the upper mixing impeller diameter, d_2 is the lower mixing impeller diameter, k_1 , k_2 are weight coefficient of the impeller.

According to the Eq. 5 and Eq. 6, we got following equation:

$$N_P = \frac{P}{\rho N^3 d^5} \tag{7}$$

Supposed $A = \frac{P}{\rho N^3}$ Eq. 7 can be expressed by Eq. 8:

$$A = N_P d^5 = N_P \left(k_1 d_1 + k_2 d_2\right)^5 \tag{8}$$

The numerical simulation results of the stirring power were listed in Table 1, when the upper and lower diameter changed, then the value of A can be calculated on the basis of the results. The value of N_P, K_1, K_2 were obtained through the nonlinear regression analysis of the SPSS software on the basis of Eq. 8.

The iterative initial value of N_P was 1.0 in nonlinear regression, because of the turbulence in stirred tank which the value of N_P was approximately 1.0. The stirring power of the upper and lower mixing impeller were assumed to equal in the initial state, so the iterative initial value of k_1 and k_2 were 0.5, respectively. The optimal solution was obtained after 9 iterations by using the SPSS software to carry out the nonlinear regression analysis. The iteration step, residual sum of squares and parameters were listed in Table 2.

As shown in Table 2, the parameter values were obtained after the nonlinear regression, the value of k_1, k_2 and N_P were 0.738, 0.299 and 1.002, respectively. So we got the following equation:

$$N_P = \frac{P}{\rho N^3 \left(0.738 d_1 + 0.299 d_2\right)^5} \tag{9}$$

The power number was related to the mixing impeller diameter, impeller rotational speed and fluid density, the value of N_P was obtained by nonlinear regression was the average value of the different mixing impeller diameter. In order to obtain the power number of the mixing impeller under different operating conditions, the numerical simulation was carried out when the impeller rotational speed was 100, 150, 200, 250, 300 and 350 rpm, respectively, according to the impeller rotational speed range (Table 3). The stirring power was obtained according to the analysis results, the power

Table 1: The stirring power consumption and the value of A

Upper mixing impeller diameter d_1 (m)	Lower mixing impeller diameter d_2 (m)	Stirring power P (W)	A
0.55	0.63	11250	0.1349
0.59	0.63	11550	0.1385
0.63	0.63	12974	0.1556
0.67	0.63	15860	0.1902
0.71	0.63	16746	0.2008
0.75	0.63	17628	0.2114
0.79	0.63	22334	0.2678
0.83	0.63	24200	0.2902
0.87	0.63	33670	0.4038
0.75	0.43	14760	0.1770
0.75	0.47	15444	0.1852
0.75	0.51	16150	0.1937
0.75	0.55	16692	0.2002
0.75	0.59	17342	0.2080
0.75	0.63	17628	0.2114
0.75	0.67	18408	0.2207
0.75	0.71	18668	0.2239
0.75	0.75	23530	0.2822

Table 2: The iteration step, residual sum of squares and parameters

The number of iterations	The residual sum of squares	Parameter		
		k_1	k_2	N_p
0	0.115	0.500	0.500	1.000
1	0.031	0.546	0.537	1.008
2	0.022	0.602	0.459	1.002
3	0.015	0.712	0.330	1.002
4	0.015	0.740	0.297	1.001
5	0.015	0.738	0.299	1.001
6	0.015	0.738	0.299	1.002
7	0.015	0.738	0.299	1.002
8	0.015	0.738	0.299	1.002
9	0.015	0.738	0.299	1.002

Table 3: The stirring power, the Reynolds number and the power number under different impeller rotational speed

Impeller rotational speed (rpm)	The stirring power (kW)	Reynolds number	Power number
100	1.96	10549	1.6382
150	5.08	15823	1.2581
200	10.05	21098	1.0500
250	17.63	26372	0.9431
300	29.65	31646	0.9179
350	46.28	36921	0.9022

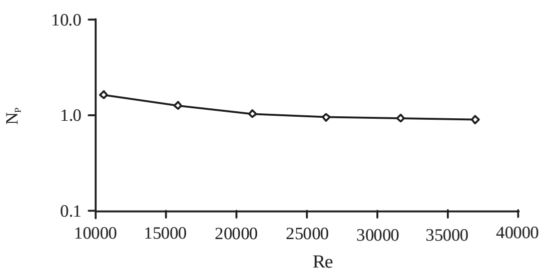

Fig. 8: The relationship between the Reynolds number and power number of the sand blender stirring device

number was calculated by using Eq. 9 and the Reynolds number was calculated by using Eq. 10. The stirring power, Reynolds number and power number were listed in Table 3. The relationship between the Reynolds number and power number was shown in Fig. 8.

$$Re = \frac{d^2 N\rho}{\mu} = \frac{(0.738d_1 + 0.299d_2)^2 N\rho}{\mu} \quad (10)$$

As shown in Fig. 8, the power number of the sand blender stirring device was decreased, when the Reynolds number ranged from 10000-40000. As the Reynolds number increased, the power number decreased slowly, the trend of the power number was in accordance with other mixing impeller (Chen *et al*., 2010), thus the result was proved to be reliable.

CONCLUSION

The baffle number and the spacing of the dual mixing impeller had less influence on the stirring power of the sand blender stirring device, but the upper and lower mixing impeller diameter had great influence on the stirring power of the sand blender stirring device. The stirring power increased along with the increase of the mixing impeller diameter. The stirring power had a large increase when the upper mixing impeller diameter over 750 mm or the lower mixing impeller diameter over 710 mm.

The weight coefficients of the upper and lower impeller diameter were obtained when the stirring power was calculated, according to the multiple combinations of the upper and lower mixing impeller diameter. The weight coefficients of the upper and lower mixing impeller were 0.738 and 0.299, respectively, which indicated that the influence of the upper mixing impeller on the stirring power was greater than that of the lower mixing impeller.

The power number and the Reynolds number were obtained, according to the numerical simulation of different impeller rotational speed. The power number decreased along with the increase of the Reynolds number and the slope of the N_P-Recurve decreased slowly, the trend of the power number was in accordance with other mixing impeller. The stirring power of the sand blender stirring device can be calculated by the N_P-Recurve and the equation of the stirring power.

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