Blend Tool Design using CFD

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Abstract

A method to utilize computational fluid dynamics (CFD) as a modeling tool to predict the mixing blend tool dynamics is presented. Blender and various tool geometries have been analyzed and computational grids have been created using commercially available CFD software. Simulations have been performed at various rotational tool speeds, treating the toner particle in air as a pseudo-homogenous single phase fluid while utilizing the K-ω turbulence model for the strongly swirling flow pattern. In addition to flow observations, the total moment of the tool surfaces and tool wall shear stress have also been measured as critical blending parameters. The tool area weighted average shear stress and integral tool shear stress have been found to respond to the various tool configuration simulated, suggesting that certain tool configurations have an increased blending functional efficiency for additive distribution and attachment.

Introduction

The coating of dry ink toners with additives is a critical part of the manufacturing process. With the trend towards smaller toner sizes, as well as the increasing ability to control both dry ink toner shape and surface, the additive blending process now plays an even greater role in determining the charging and the flow functionality of the dry ink. The blenders commonly used for toner additive blending are fluidizing mixers wherein the high rotational speeds of the mixing tools are utilized to disperse and attach the various additives to the dry ink toner surface. A critical outcome of this mixing process is the additive adhesion to the dry ink toner surface. In the one extreme, additives can be completely buried into the dry ink toner surface so that the flow functionality is not achieved. In the other extreme, the additives are not sufficiently attached such that they become contaminants in the xerographic system impairing the development functionality. The primary inputs into the additive blending process are the uncoated particles, various additive quantities, mixing tool type, mixing speed, and mixing time. An increased understanding of the fluid dynamic effects of various mixing tool types is desired in order to leverage the available manufacturing technologies to achieve functional material performance, to provide manufacturability, and to indicate technical direction for the following generations of material designs.

Objectives and approach

A CFD commercial software package, FLUENT, was used as a modeling tool to predict blend tool dynamics. The goals are to generate blending power curves to compare with the experimental results; to understand the flow pattern and focus on high shear region flow; and to improve the blend tool design to generate more shear and less impact to the toner.

A pseudo-homogenous model was assumed i.e., treating toner particle in air as a "pseudo-homogenous" single phase fluid. The volume fraction of the toner ε_s is 14%. So the density of the mixture is 0.17 g/cm^3. The viscosity of the mixture μ_{mix} is 6×10^{-4} kg/(m-sec), which is calculated according to Hawksley's expression [1]:

$$\mu_{mix} = \mu_{air} \exp[4.1\varepsilon_s/0.64 + (1-\varepsilon_s)] \quad (1)$$

The blades are rotated clockwise at a constant angular speed from top view. The inner surface of the vessel and the surface of the blades are 'rough', i.e., there is no relative motion of the fluid on the surfaces of the vessel and the blades. Heat transfer was ignored – focusing on the flow pattern. Gravity is ignored. The simulation was performed at 1.0k, 1.5k, 2.0k, 2.5k, and 3.0k rpm. K- ω turbulence model was used to stress the strong swirl flow pattern). MRF (Multiple Reference Frames) method is used for the rotation of the blades. Convergence criteria was set to 1×10^{-5} relative error for the residuals of continuity, velocities, k and ω. The moment of the blades was monitored to confirm the convergence. Model size: 1.6 million cells. Prism cells were used in the boundaries of blades and vessel to capture the velocity gradients. The power draw and shear on the blades were calculated in the post processing.

CFD results and discussions

As a baseline, the standard 10L Henschel tool [2] will be discussed first. L-shaped and T-shape high riser tools will be discussed and compared with the standard 10L Henschel tool. Optimization (parametric design) of high riser tool will be followed. Sickle tool will be compared with the optimized high riser tool. An optimized tool will be presented in the end.

Standard 10L Henschel tool

The toner flow pattern of a Henschel tool toner blender with a baffle is shown in Fig.1-2. It shows the toner velocity in-plane flow at 2000rpm spindle speed. In Fig.1, the velocity of toner is projected onto the vertical plane. This projected plot shows the vertical and radial combined velocity vector, i.e., the rotational component is ignored, to emphasize the blending effect. The baffle plays a significant role in changing the flow pattern. It stops the rotation of the toner and forces the toner to fall to the lower part of the mixing container. This action is helpful in toner mixing. The toner rises from side pushed by the rotating blades, and then falls from the center of the top. Fig.2 shows the toner velocity projected onto the horizontal plane. This plot emphasizes the rotational component. The speed is higher away from the center. The toner speed on the blade is the same as the blade speed, which is consistent with the 'rough' surface assumption. The plane located on the cross section of the middle blade.

Figure 1. *flow pattern in vertical plane (10L standard Henschel tool)*

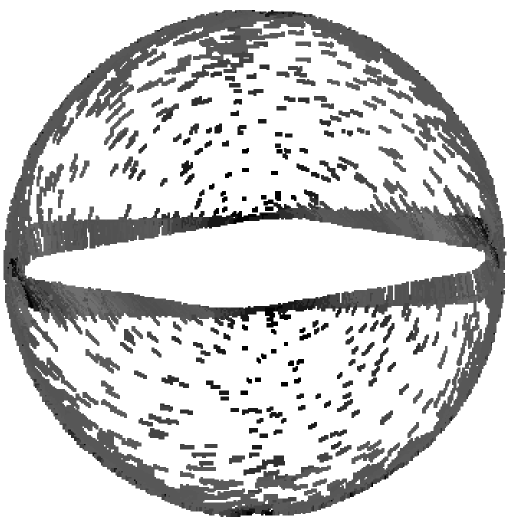

Figure 2. *flow pattern in horizontal plane (10L standard Henschel tool)*

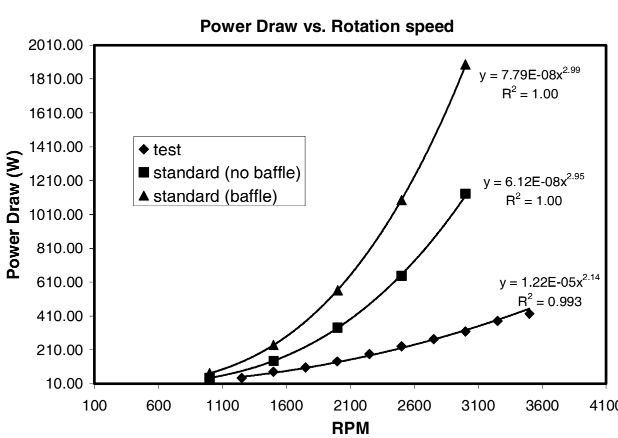

Figure 3. *power draw in toner blending (10L standard Henschel tool)*

The power draw is calculated from the total moment of the tool surfaces. Fig.3 includes the power draw with and without baffle cases, together with the test results. The results show that the power draw is proportional to the cubic of the rotation speed, which agrees with the liquid mixing law [3]. The test results show that the exponent of the power relation is between 2 to 3. The granular behavior of the toner reduces the power index. The existence of the baffle increases the power draw.

L-shape high riser tool

Fig.4 shows the in-plane flow pattern of a high riser tool at 2000rpm. The high riser tool pushes the toner up from the side of the vessel. The toner falls back from the center with the help of the baffle.

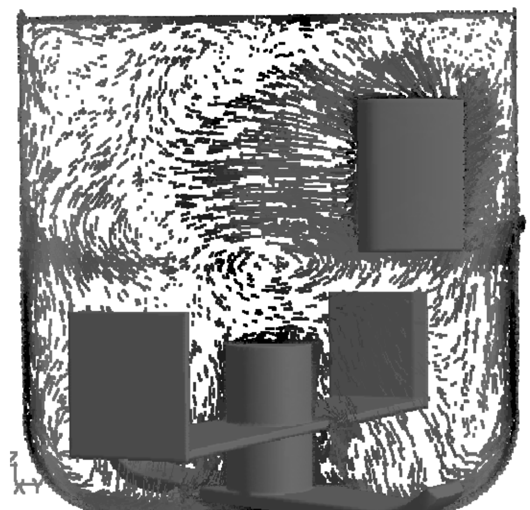

Figure 4. *flow pattern in vertical plane (L-shape high riser tool)*

The power draw in high riser tool blending is much higher than that of a standard tool, as shown in Fig.5. It's expected since the hit angle of it is much larger than that of the standard tool. It causes more toner to be pushed up, so larger reaction force will be on the blade. Higher power draw will cause higher temperature increase and higher power input in blending, which were observed in testing.

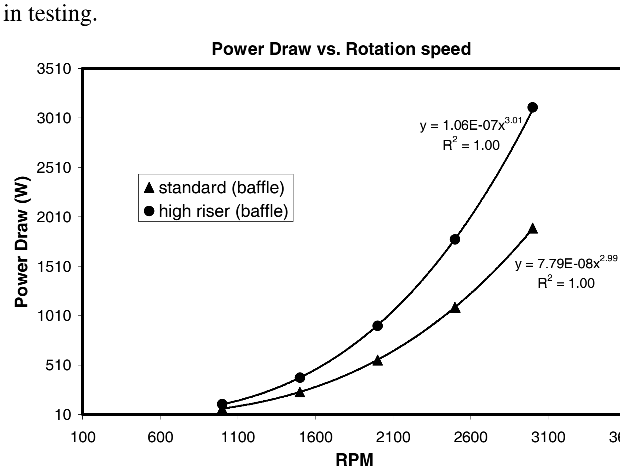

Figure 5. *power draw comparison between Henschel and high riser tools*

The magnitude of wall shear stress on the rotating tool was averaged and plotted in Fig.6. It was integrated over the whole surface area of the tool and plotted in Fig.7. The wall shear was plotted against the net power draw. Both figures show that for the same net power draw, the high riser tool case has smaller wall shear: smaller area weighted averaged wall shear stress and smaller integral of shear stress on the blade. It may be an indication that the blending efficiency of the high riser tool is lower than that of the standard tool in the assumption that the blending efficiency increases with the shear stress magnitude.

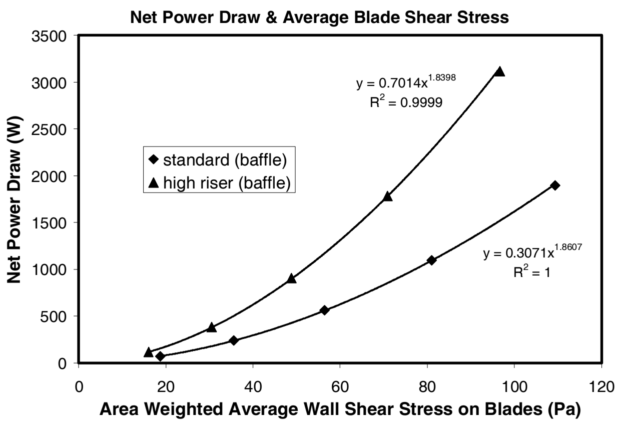

Figure 6. *area weighted average wall shear stress on tools*

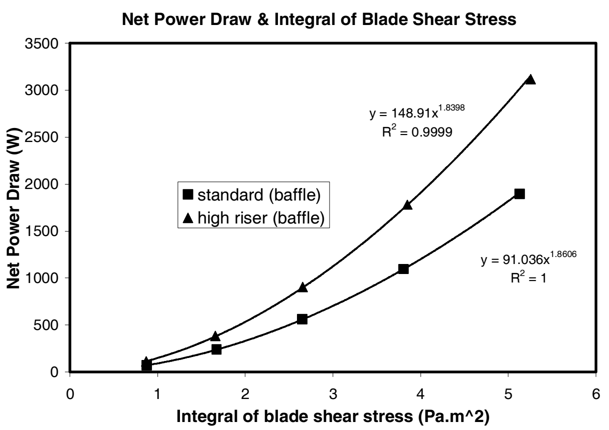

Figure 7. *integral of wall shear stress over area on tools*

T-shape vs. L-shape high riser tool

The T-shape high riser tool has much higher bending stiffness comparing to the L-shape tool. So it has mechanical advantages over the L-shape tool. The CFD simulation results show that the wall shear stress of L and T shaped high riser tools are almost the same at the same power draw level. So the blending efficiency of them is the same. It suggests that it's a reasonable option by replacing the L-shape tool with the T-shape tool because of its mechanical advantages. Fig.8 shows the 3D geometry of L-shape and T-shape toner blending tools.

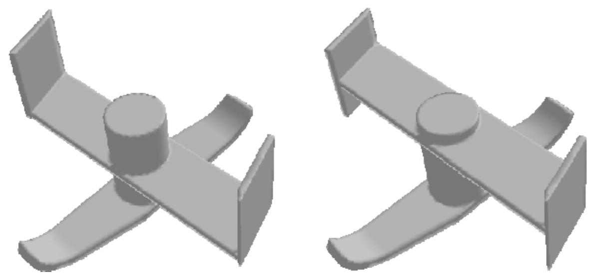

Figure 8. *3D geometry of L-shape and T-shape toner blending tools*

High riser tool optimization by parametric design

The DOE control factors in the parametric design are pre-assumed to be hit angle and riser width, which are schematically shown in Fig.9.

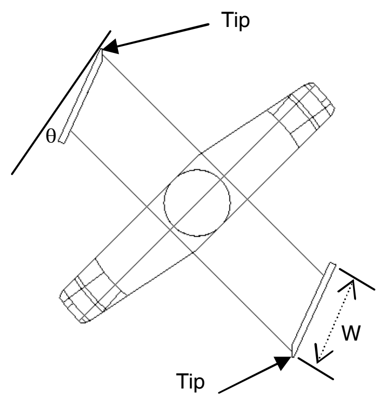

Figure 9. *schematic drawing of DOE control factors in high riser tool*

The DOE simulation is based on T-shape high riser tool with variations of $\Delta w = \pm 20\%$ and $\Delta\theta = \pm 3.5^\circ$. Five cases studied are: hrm1: base case; hrm2:+w-θ; hrm3:-w+θ; hrm4:+w+θ; hrm5:-w-θ. From case to case, the geometry varies, but the gap between the tip of the blade and the wall of the vessel is kept the same.

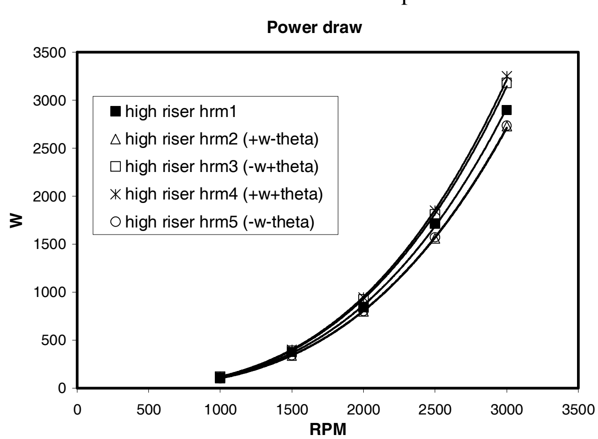

Figure 10. *power draw for high riser tool in different hit angle and riser width*

The power draw plot in Fig.10 shows that cases hrm3 and hrm4 have higher power draw: bigger hit angle θ, higher power draw. Power draw is not sensitive to the width of the blade.

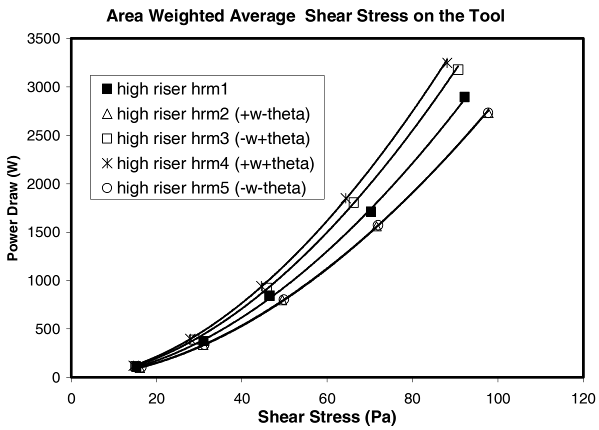

Figure 11. *area weighted average shear stress for T-shape high riser tool*

Case hrm2 and hrm5 show higher area weighted average shear stress, both of them have smaller hit angle, as shown in Fig.11.

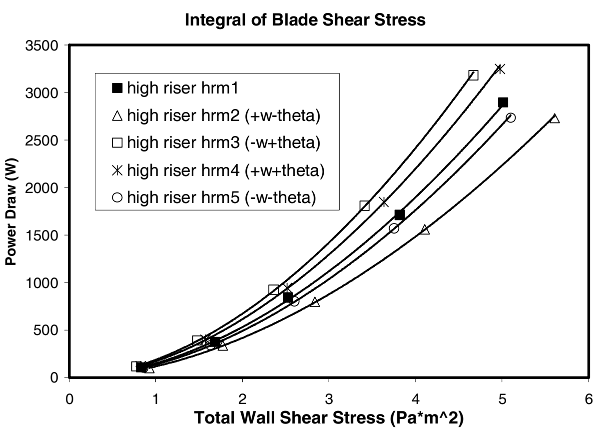

Figure 12. *integral of wall shear stress over area on the T-shape tool*

Since case hrm2 has larger riser width, it has the larger integral shear stress than that of case hrm5. DOE results show that smaller hit angle and larger blade area are favored in toner blending. See Fig.12.

Sickle tool vs. optimized high riser tool

Fig.13 is a schematic drawing of sickle tool. Lower power draw and lower temperature increasing in toner blending process were observed. It's interesting to know its blending efficiency in term of wall shear stress.

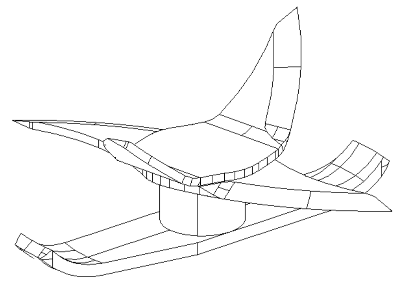

Figure 13. *a schematic drawing of a sickle tool*

The sickle tool has lower power draw at the same RPM than that of the optimized high riser tool, i.e., the T-shape hrm2 (-θ+w) high riser tool. See Fig.14.

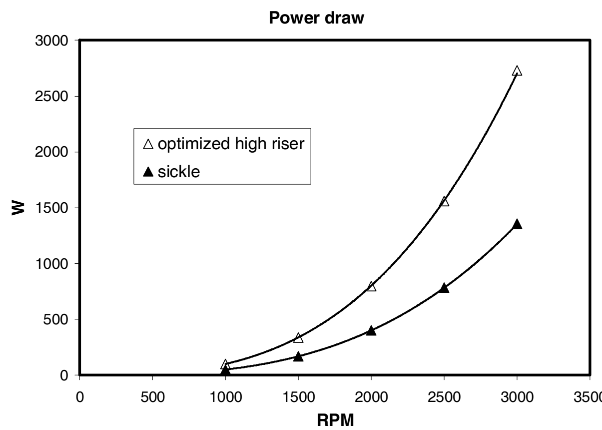

Figure 14. *power draw curves of sickle tool and optimized high riser tool*

The area weighted average shear stress on the sickle tool is much higher than that of the optimized high riser tool for the same power draw, so it's a blending efficient tool.

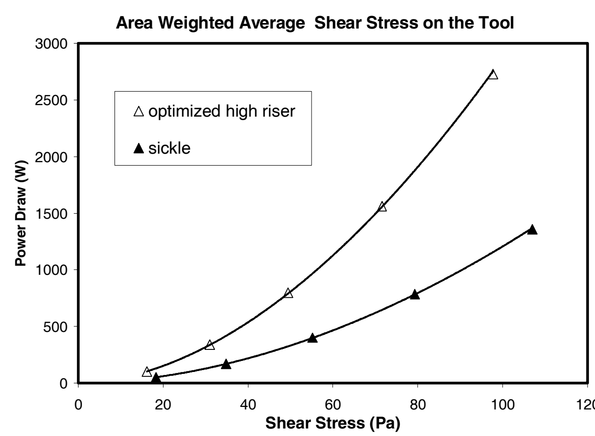

Figure 15. *area weighted average wall shear stress of sickle tool and optimized T-shape high riser tools*

The Integral of blade shear stress on the surface area of sickle tool is still higher than that of the optimized high riser tool for the same power draw level, but the difference is not obvious. It’s because the sickle tool has much smaller surface area. See Fig.16.

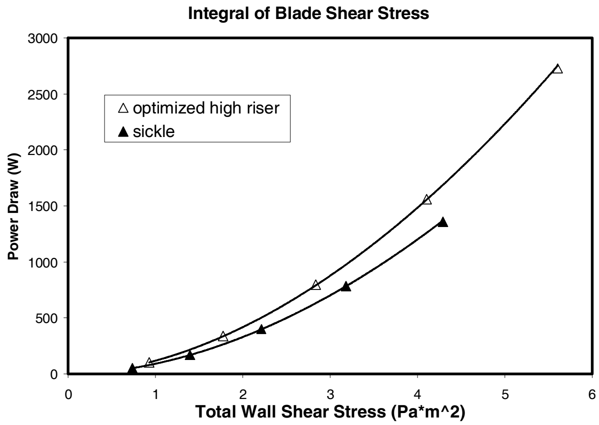

Figure 16. *integral of shear stress over the tool surface areas*

An optimized tool

A virtually optimized tool was designed and analyzed. The power draw curve is closer to the optimized high riser tool, as shown in Fig.17. It’s expected because of its design incorporates geometry from the optimized high riser tool.

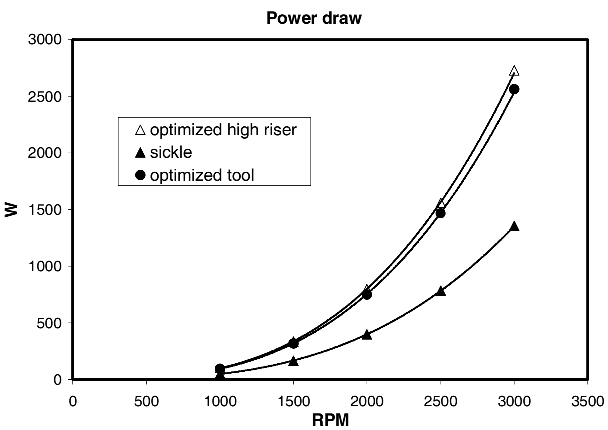

Figure 17. *power draw curves of optimized, high riser and sickle tools*

The area weighted average shear stress of the sickle tool is higher than that of the optimized high riser and optimized tools. See Fig.18.

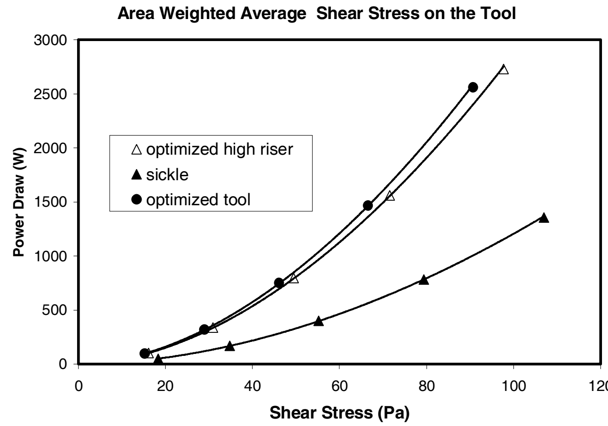

Figure 18. *area weighted average shear stress of optimized, high riser and sickle tools*

The optimized tool has the highest integral wall shear stress. For the same power draw, the total shear is highest for the new tool. i.e., it will be the most blending efficient tool among them. See Fig.19. Also, since it has much larger blade area, the total wall shear of it will be 50% more than that of the sickle tool at the same RPM (not at the same power draw), keeping in mind that each curve includes five levels of rotational speed: 1.0k, 1.5k, 2.0k, 2.5k and 3.0k rpm.

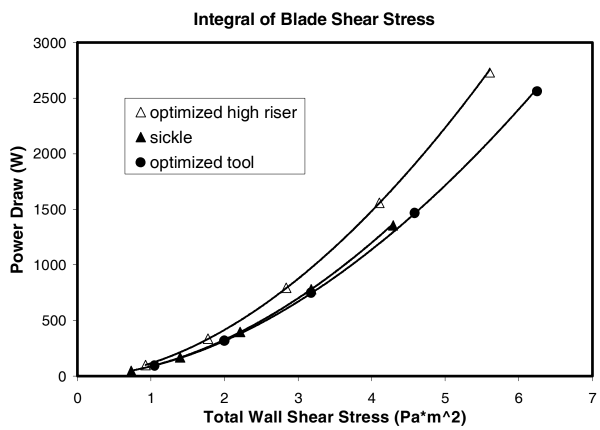

Figure 19. *Integral of wall shear stress over the surface areas of optimized, high riser and sickle tools*

Summary

It seems the baseline high riser tool doesn’t have higher shear stress than that of the standard Henschel tool. The T-shape high riser tool has the same blending behavior as that of the L-shape high riser tool. The former has higher bending stiffness than that of the latter. The toner is pushed up from outer part of the vessel (close to the wall) by the blades and return from the center of the top. The baffle stops the circular movement of the toner and forces the toner to drop to the lower part of the vessel, thus enhance the blending. DOE results show that smaller hit angle and larger blade width is favored in blending efficiency for the high riser tool. The sickle tool has the highest area weighted average shear stress. The optimized tool has the highest blending efficiency and reflects the opportunity of incorporating virtual design into our current processes.

References

[1] R. L. Whitmore, The sedimentation of suspensions of spheres, *Br. J. Appl. Phys.* **6** 239-245 (1955)

[2] Henschel Product Brochure

[3] Handbook of Industrial Mixing: Science and Practice, Edward L. Paul (Editor), Victor Atiemo-Obeng (Editor), Suzanne M. Kresta (Editor)

Author Biography

Jing Li received his BS in material science from Tsinghua University, China (1987) and his PhD in Mechanical Engineering from the University of Rochester (2001). Dr. Li is a research scientist and senior engineering specialist in the area of mechanical simulation and testing at XEROX Corporation, focused on structure, thermal and CFD simulation and vibration test. He has published over 20 professional papers in international journals and conferences.

Samir Kumar received his Ph.D. in Chemical Engineering from the Ohio State University. He joined Xerox's Consumables Development and Manufacturing Group in 1993 and is currently an Area Manager responsible for upstream Toner/Developer Designs and process technology. Samir was the leader for advancing the additive blending process for both conventional and chemical toners at Xerox. He has designed several novel blend tools that are used for manufacturing toners. He has authored 8 external technical papers and has over 20 U.S. patents.

Paul Casalmir received his BS in Biomedical Engineering and his BS in Chemical Engineering from Rensselaer Polytechnic Institute, and his MS in Computer Integrated Manufacturing from Rochester Institute of Technology. He is currently a Product Delivery Manager in Xerox's Consumables Development and Manufacturing Group, responsible for bringing new materials to market. Paul has 9 patents in the areas of materials composition and powders processing technology.