International Symposium
On Turbulence and Shear Flow
Phenomena (TSFP-9)
June 30 - July 3, 2015 *Melbourne, Australia*

DRAG REDUCTION PERFORMANCE OF FDR-SPC (FRICTIONAL DRAG REDUCTION SELF-POLISHING COPOLYMER)

Inwon Lee
GCRC-SOP (Global Core Research Center for Ships and Offshore Plants)
Pusan National University
2, Busandaehak-ro 63beon-gil, Guemjeong-gu, Busan 609-735, Korea
inwon@pusan.ac.kr

Hyun Park
GCRC-SOP (Global Core Research Center for Ships and Offshore Plants)
Pusan National University
2, Busandaehak-ro 63beon-gil, Guemjeong-gu, Busan 609-735, Korea
hyunpark@pusan.ac.kr

Ho Hwan Chun
GCRC-SOP (Global Core Research Center for Ships and Offshore Plants)
Pusan National University
2, Busandaehak-ro 63beon-gil, Guemjeong-gu, Busan 609-735, Korea
chunahh@pusan.ac.kr

ABSTRACT

In this study, a novel skin-friction reducing polymer named FDR-SPC (Frictional Drag Reduction Self-Polishing Copolymer) has been synthesized. The drag reducing functional radical such as PEGMA (Poly(ethylene) glycol methacrylate) has been utilized to participate in the synthesis process of the SPC. The types of the baseline SPC monomers, the molecular weight and the mole fraction of PEGMA were varied in the synthesis process. In the high-Reynolds number flow measurement with a flush-mounted balance and a LDV (Laser Doppler Velocimeter), the skin friction of the present FDR-SPC is found to be smaller than that of smooth plate in the entire Reynolds number range, with the average drag reduction efficiency being 13.5% over the smooth plate.

INTRODUCTION

The reduction of frictional drag of turbulent boundary layer is of great importance for the fuel economy of ship. Along with the development of hull form optimization technique, the wavemaking resistance has become less than 20% of the total drag of most modern ships. Therefore, the advantage from the reduction of the remaining frictional drag would be enormous. The fuel consumption of global ocean shipping in 2003 was estimated 2.1 billion barrel/year (Corbett and Koehler, 2003), which corresponds to approximately 200 billion US$/year. Thus, 10% reduction of frictional drag would lead to saving of 16 billion US$/year. The skin frictional drag is closely associated with the coherent structures, e.g. hairpin vortices in the turbulent boundary layer flow. Various control strategies toward the attenuation of the drag-inducing flow structure have been proposed during several decades. One of the most effective drag reduction strategies is the polymer injection, which was first introduced by Toms (1949). Toms (1949) found that addition of few ppm of a high molecular weight polymer to a turbulent water flow can result in large (up to 80%) reduction of skin friction drag. Added long chain polymer molecule extracts the turbulent energy out of the adjacent flow by coiling its chain structures and then releases the energy by becoming stretched back in the shear flow. The turbulent energy transfer between the freestream and the near-wall flow is thus interfered, leading to a significant skin friction reduction. This is named Toms effect after who discovered it. The polymer injection has been put into practice for the pipeline transportation of petroleum, demonstrating one of the most effective examples of drag reduction.

It has been suggested that the polymer injection be applied to the frictional drag reduction for ships. There have been various researches to exemplifying the drag reduction efficiency of polymer injection in turbulent boundary layer (Brasseur *et al.* 2005, Li *et al.* 2008, Somandepalli *et al.* 2010). From the aspect of implementation, however, the polymer injection is impractical for ship application. This is because it necessarily requires the injection holes to be installed onto the hull surface, which would cause significant structural strength issues. As a feasible alternative to the polymer injection method, Yang *et al.* (2014) proposed a PEO-containing AF paint. They reported the release of PEO, the well-documented drag reducing agent leading to Toms effect, from the surface of coating. It was found that the

PEO-mixed paint exhibited significant drag reduction efficiency in excess of 10% from various lab tests. In their paint, however, the PEO powders were physically mixed with the paint matrix, thereby giving rise to an increase in surface roughness and rapid release associated with the solubility of PEO in water. These factors may be detrimental to the longevity of drag reduction performance.

Table 1 Synthesis parameters and drag reduction effects for various SPCs

Substrates	PEGMA M.W.	PEGMA mol%	Drag Reduction (%)
SPC 13	-	0	**1.291**
PRD1-1	A	X	**1.741**
PRD1-2	A	Y	**2.557**
PRD1-3	A	Z	**0.117**
SPC 10	-	0	**5.49**
PRD2-1	A	X	**8.54**
PRD2-2	A	Y	**12.82**
PRD2-3	A	Z	**15.42**
PRD3-1	B	X	**15.94**
PRD3-2	B	Y	**14.44**
PRD3-3	B	Z	**10.06**

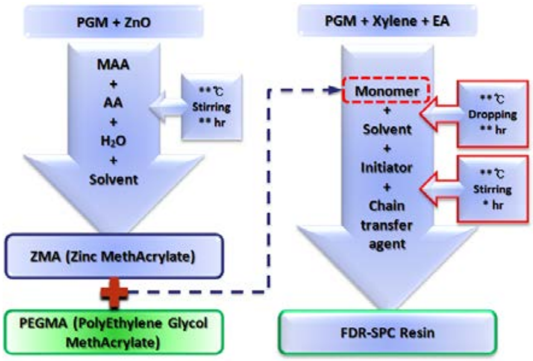


Figure 1 Synthesis process diagram of FDR-SPC

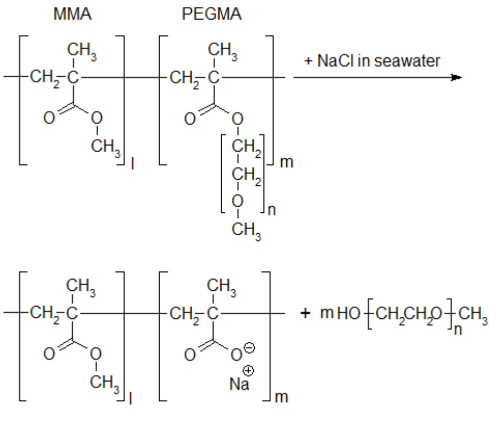


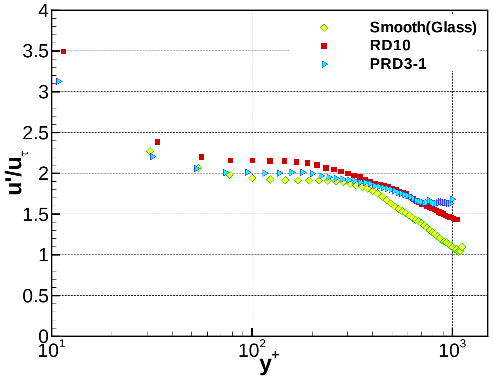
Figure 2 Hydrolysis reaction of FDR-SPC

SYNTHESIS OF FDR-SPC

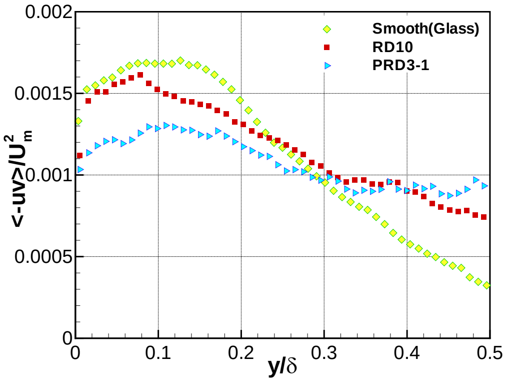
With a view to overcoming the drawbacks of the PEO-mixed paint in the previous research, a novel FDR-SPC is first synthesized in this study. Synthesis process consisted of the various reactions shown in Fig. 1. The drag reducing functional radical such as PEGMA (Poly(ethylene) glycol methacrylate) has been utilized to participate in the synthesis process of the SPC. Figure 2 illustrates the release mechanism of PEO from the hydrolysis reaction between the FDR-SPC and seawater. The types of the baseline SPC monomers, the molecular weight and the mole fraction of PEGMA were varied in the synthesis process.

PERFORMANCE OF FDR-SPC IN A LOW REYNOLDS NUMBER FLOW

The resulting SPCs were coated to the substrate plates for the subsequent hydrodynamic test for skin friction measurement. In a low-Reynolds number flow measurement using PIV (Particle Image Velocimeter), a significant reduction in Reynolds stress was observed in a range of specimen, with the maximum drag reduction being 15.9% relative to the smooth surface for PRD3-1, as shown in Table 1. Figure 3 shows the profiles of the streamwise turbulent intensity and the Reynolds stress. It is obvious that those turbulent quantities significanty decreased in the case of PRD3-1, corroborating the presence of Toms effect from the present FDR-SPC.



(a) Streamwise turbulence intensity



(b) Reynolds stress

Figure 3 Comparison of turbulent quantities in low-Reynolds number flow for FDR-SPC

PERFORMANCE OF FDR-SPC IN A HIGH REYNOLDS NUMBER FLOW

The present FDR-SPC was subsequently used as a binder for the FDR AF (AntiFouling) coating for marine application. The FDR AF coating consisted of FDR-SPC, antifouling pigment such as cuprous oxide (Cu_2O) and various additives. Measurement of the skin friction of the present FDR-SPC and the FDR AF coated surfaces was carried out in a high-Reynolds number flow measurement with a flush-mounted balance and a LDV (Laser Doppler Velocimeter), as depected in Fig. 4 It is found that the FDR-SPC showed smaller skin friction than the smooth plate in the entire Reynolds number range, with the average drag reduction efficiency being 13.5% over the smooth plate. The FDR-AF (Anti-Fouling) coating manufactured from the present FDR-SPC exhibits drag reduction efficiency of about 20% over the conventional AF coatings, as shown in Tables 2 and 3, and Fig. 5.

Figure 4 Photos of the high-speed water tunnel, flush-monted balance and the samples of FDR-SPC and FDR-AF coatings

Table 2 Comparison of skin frictional drag between FDR-SPC and uncoated surface

U(m/s)	Re_x ($\times10^{-6}$)	Uncoated (Smooth)	FDR-SPC (PRD3-1)	
		C_F ($\times10^{-3}$)	C_F ($\times10^{-3}$)	DR(%)
4	6.85	2.977	2.700	**9.30**
6	10.28	2.829	2.471	**12.65**
8	13.71	2.708	2.363	**12.74**
10	17.14	2.646	2.246	**15.12**
12	20.56	2.580	2.212	**14.26**
14	23.99	2.491	2.132	**14.41**
16	27.42	2.490	2.087	**16.18**

Table 3 Comparison of skin frictional drag between FDR-AF and baseline AF

U(m/s)	Re_x ($\times10^{-6}$)	Baseline AF	FDR-AF (T-5)	
		C_F ($\times10^{-3}$)	C_F ($\times10^{-3}$)	DR(%)
4	6.85	3.708	2.935	**20.85**
6	10.28	3.472	2.813	**18.98**
8	13.71	3.415	2.677	**21.61**
10	17.14	3.431	2.551	**25.65**
12	20.56	3.467	2.485	**28.32**
14	23.99	3.392	2.374	**30.01**
16	27.42	3.362	2.279	**32.21**

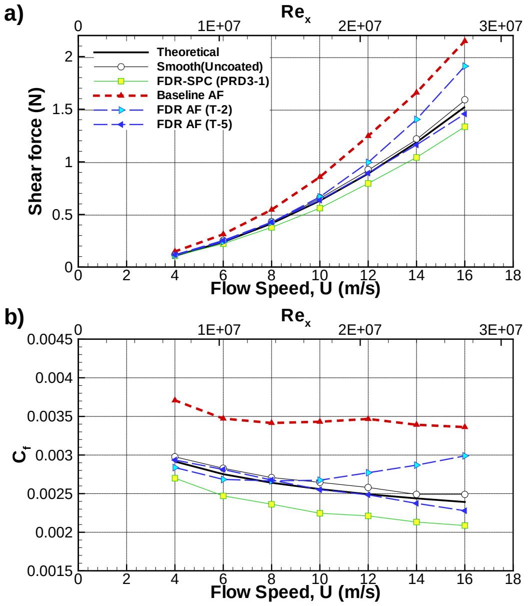


Figure 5 Comparison of frictional drag in high Reynolds number flow for FDR-SPC and FDR AF coatings

Figure 6 exhibits ther profiles of turbulence intensity for FDR-SPC in comparison with the smooth surface case. For lower velocity, the difference of turbulence intensity profiles is not significant. As the velocity increases, however, the turbuelence intensity for FDR-SPC becomes significantly lower than the smooth surface in the near-wall region. In addition, the peak location of the turbulence intensity moves farther away from the wall in the case of FDR-SPC. These observation corroborates the Toms effect based on chemical reaction at the surface of the coating.

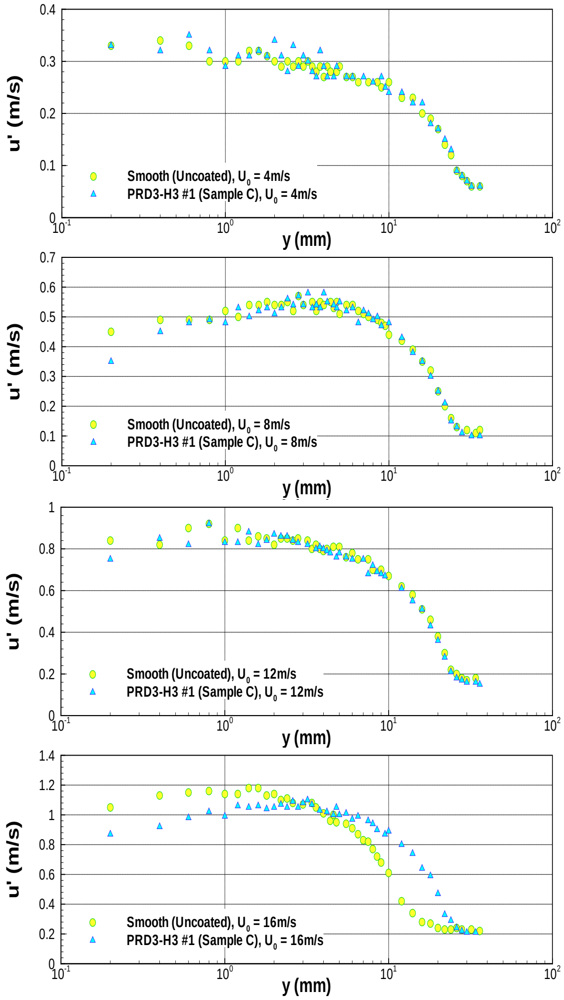


Figure 6 Comparison of turbulence intensity profiles for FDR-SPC and smooth surface

LONG-TERM PERFORMANCE TEST OF FDR-AF

It is worthwhile to mention that all of the above the frictional reduction performaces are pertaining to the freshly coated surface, *i.e.*, the initial condition of the coating. Considering the typical lifetime of the AF coating to be three to five years, the long-term FDR performance is also of great concern from the view point of real applicability of the present technology. As the coating based on SPC (Self-olishing Copolymer) contines to be in contact with seawater, erosion processes based on the hydrolysis reaction takes place so that the layers of coating are peeled-off and dissolved into water. During those processes, the PEGMA FDR radical is supposed to released constantly into the water, thereby accomplishing a long-term FDR performance.

Since a long-term frictional drag assessment in the circulating water tunnel is impractical, a rotor tester was fabricated in this study, as shown in Fig. 7. In this apparatus, up to eight rotors are rotated by the motors in the seawater tank (shown upper left in Fig. 7) during several months at a rotational speed of 500rpm. Each rotor had the same dimension with the diameter and the height being 320mm and 310mm, respectively. This gave the tangential speed of 16.3 knots, which closely approximates typical speed of marine vessels. The rotors are driven five days out of a week to reproduce the duty cycle of 70%. After one month of rotation in the seawater tank, each rotor was then moved to the rotor measurement appratus (shown upper right in Fig. 7) to measure the torque.

Figure 7 Photos of rotor test apparatus and rotors with different coatings

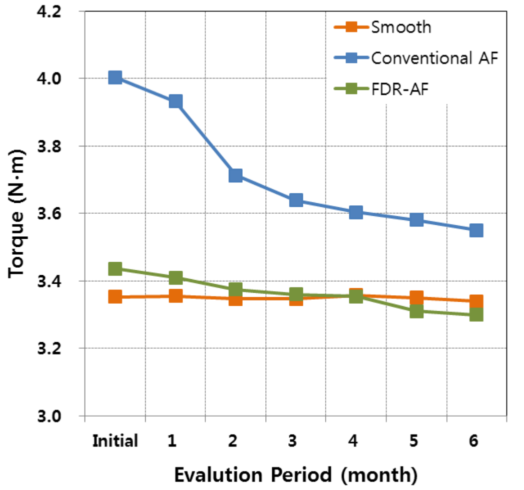


Figure 8 Long-term temporal variation of torques of rotors with varying surface conditions

The six-months torque time history is plotted in Fig. 8. It is evident that the present FDR AF coating maintains the FDR performance after the continued operation. Furthermore, it is remarkable the FDR AF shows exhibits smaller torque compared with the smooth (uncaoted) rotor (shown lower left in Fig. 7) in spite of the obvious increase of surface roughness over smooth surface. The comparable skin friction of FDR AF compared with the smooth surface is also consistent with the initial FDR performance obtained in a high Reynolds number turbulent boundary layer, plotted in Fig. 5.

ACKNOWLEDGEMENTS

This work was supported by National Research Foundation of Korea (NRF) grant of the Korea government (MSIP) through GCRC-SOP (No. 2011-0030013)

REFERENCES

Brasseur, J. G., Robert, A., Collins, L. R. and Vaithianathan, T., 2005, “Fundamental Physics Underlying Polymer Drag Reduction, from Homogeneous DNS Turbulence with the FENE-P Model,” *2nd International Symposium on Seawater Drag Reduction*, Busan, Korea, 23-26 May 2005, pp.477-487

Corbett, J. J. and Koehler, H. W., 2003, “Updated emissions from ocean shipping,” *J. Geophysical Research*, vol. 108, no. D20, pp. ACH 9-1 ~ 9.13

Li, C. F., Wu, G. F., Feng, X. D., Zhao, Z. G., Sureshkumar, R. and Khomami, B., 2008, “Ejections and Bursts in a Low Drag Reduction Turbulent Channel Flow of Dilute Polymer Solutions,” *Proceedings of the 12th Asian Congress of Fluid Mechanics*, 18-21 August 2008, Daejeon, Korea, Paper No. 12acfm-257

Schultz, M. P., 2004, “Frictional Resistance of Antifouling Coating System,” *Trans. ASME J. Fluid Eng.*, vol.126, pp. 1039-1046

Somandepalli, V. S. R., Hou, Y. X. and Mungal, M. G., 2010, “Concentration flux measurements in a polymer drag-reduced turbulent boundary layer,” *Journal of Fluid Mechanics*, vol. 644, pp.281-319

Toms, B., 1948, “Observation on the flow of linear polymer solutions through straight tubes at large Reynolds numbers,” *Proc. Intl Rheol. Congr*. vol. 2, pp.135–141.

Yang, J. W., Park, H., Chun, H. H., Ceccio, S. L., Perlin, M. and Lee, I., 2014, Development and performance at high Reynolds number of a skin-friction reducing marine paint using polymer additives, *Ocean Engineering*, vol. 84, pp.183-193