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# The Effect of In-Flow and Counter-Rotating Props on the Efficiency of Azimuthing Thrusters

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## Abstract

The role of the Coanda Effect in the efficiency of azimuthing thrusters is well established, and thruster manufacturers have responded by producing "tilted axis" thrusters, generally 7 to 8 degrees from horizontal. However, tilting the prop axis also increases the criticality of both thruster In-Flows and the direction of prop rotation.

We used full-scale CFD modelling to examine the effects of thruster inflows and prop counter-rotation on the efficiency of ducted, tilted axis, azimuthing thrusters mounted on two different drillship hulls.

## Abbreviations & Definitions

| | |
|---|---|
| CFD | Computational Fluid Dynamics |
| Coandă Effect | "The tendency of a jet of fluid emerging from an orifice to follow an adjacent flat or curved surface and to entrain fluid from the surroundings so that a region of lower pressure develops." -Henri Coandă |
| MODU | Mobile Offshore Drilling Unit, e.g. jack-up, semi-submersible or drillship |
| Net Effective Thrust | The net thrust vector in the horizontal plane from a ducted, azimuthing thruster. |
| Open Water Thrust | Thrust without a hull attached |
| SG | Specific Gravity |
| Thruster Efficiency | Net Effective Thrust of a hull-mounted thruster relative to Open-Water thrust. |

## Introduction

Diamond Offshore has created a proprietary drillship design called The Floating Factory ("FF"), an "Eighth Generation" Mobile Offshore Drilling Unit (MODU), with the goal of radically reducing the overall cost of drilling and completing offshore oil and natural gas wells.

**Figure 1: Diamond Offshore Drilling *Floating Factory* Drillship**

One of the central elements of the FF design is improved station-keeping efficiency, both to increase drilling up-time, and to reduce fuel consumption. To that end, we specified azimuthing thrusters with:

- 5500 kW input power
- Large, low-speed propellers (e.g. 4.2 or 4.3 M diameter)
- 7-to-8 degree down-angle
- Propellers optimized for 4 knots in-flow current

Diamond commissioned the Marine Institute of the Netherlands (MARIN) to perform tow-tank and wave basin tests of the FF design. However, the only scale-model thrusters readily available (see Figure 2) differed significantly from the specified Floating Factory thrusters:

- Horizontal shaft with 5 degree tilted Kort nozzle
- Different prop
- Incorrect prop-tip clearance
- Incorrect Kort nozzle

Making accurate scale models would have delayed testing and would have been prohibitively expensive, and in any case would have suffered from very large scale-effects at any practical ship scale. Consequently, the hull was scaled to the diameter of the available model propeller, and the model-scale thrust curve was adjusted to match the thrust curve of a preferred down-angle thruster.

Because of the compromises inherent in model-scale thrusters, it is not practical to use tank test data to determine under-hull thruster performance.


**Figure 2: MARIN Tow-Tank Test Model (1:28.93 scale) with thrusters.**

Diamond subsequently commissioned DNV-GL to perform a Dynamic Positioning Analysis for several thruster configurations for the Floating Factory design. For under-hull thruster performance and efficiency, DNV relied on the seminal CFD work by Bulten and Stolenkamp [(1)] on thruster-hull interaction, which was presented at the MTS-DP Conference in October, 2016.

Here are the thruster efficiencies from the DNV-GL DP study for the Floating Factory:

**Table 1: DNV Thruster Efficiency on Floating Factory**

| Thruster Efficiency vs. Heading (DNV DP Analysis 4020.03 Rev. A) | | | | | | |
|---|---|---|---|---|---|---|
| Thruster / Heading | T1 | T2 | T3 | T4 | T5 | T6 |
| 0 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| 30 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| 60 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| 90 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| 120 | 0.97 | 0.97 | 0.97 | 0.85 | 0.84 | 0.89 |
| 150 | 0.97 | 0.97 | 0.97 | 0.79 | 0.79 | 0.82 |
| 180 | 0.97 | 0.97 | 0.97 | 0.79 | 0.79 | 0.79 |
| -150 | 0.97 | 0.97 | 0.97 | 0.79 | 0.79 | 0.82 |
| -120 | 0.97 | 0.97 | 0.97 | 0.84 | 0.85 | 0.89 |
| -90 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| -60 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |
| -30 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 | 0.97 |

Thruster headings in the DNV report reflect *counter-clockwise* (CCW) thruster rotation viewed from the top; for example, at 0 degree heading, the thruster intake is from the bow, and the prop wash is directly towards the stern. At 30 degree heading, the thruster intake is pointed towards the port forward quarter, and the prop wash is pointed towards the starboard aft quarter.

Note that the work of Bolten & Stoltenkamp concentrated on prop-wash Coanda Effect of down-angle thrusters, but did not consider two factors which we considered to be potentially significant:

(1) the hydrodynamic effects of hull shape on the *intake flow,* and
(2) the effect of prop rotation direction.

The fact that, for example, the DNV study showed *all thrusters* to be 97% efficient *at all headings between 0 and +/- 90 degrees* did not comport with (a) our field experience with the *Blackship* drillships (Gusto P-10000 design), (b) our previous CFD studies of under-hull thrusters, or (3) our intuition about under-hull fluid flows.

For example, on the Diamond *Blackship* drillships, a Gusto P-10000 design with right-hand propeller rotation, the thrusters exhibited signs of significant asymmetries, particularly at high vessel speeds:

- the *starboard* thrusters vibrate more than the port thrusters at high vessel speeds, and
- the vessel wake at high vessel speeds is consistently asymmetrical.

Figure 3 (below) shows the wake behind *Ocean Blackhawk* transiting at about 12 knots (~70% power) across the Indian Ocean. Note the clear evidence of a Von Kármán Vortex Street on the starboard side of the wake.

**Figure 3: Wave of *Ocean Blackhawk* Transiting Indian Ocean at ~12 knots, 70% power, 7 degree down-angle thrusters**

Since Diamond Offshore have extensive experience with Computational Fluid Dynamics (CFD) modelling of under-hull thruster behaviour, we decided to do whole-vessel simulations in CFD to confirm the thruster efficiency numbers used in the DP Analysis, and particularly to understand the role of propeller rotation direction in thruster efficiency.

## CFD Models

We modelled Azipod DZ-1400P thrusters using a precise 3D model (including the correct prop, optimized for 4 knot inflow) provided by the manufacturer. The Azipod DZ1400P is a potted motor thruster with 5500 kW input power, a 4.3M diameter prop, and an 8-degree down-angle prop shaft, which meets the specification for Floating Factory thrusters.

Fluid was DODI Standard Sea Water (SG = 1.025).

We assume that CFD results would be similar for conventional gear-driven thrusters with the same down-angle, propeller specification and rotation, as the only differences between thruster efficiencies would then be the hydrodynamic efficiencies of the housings, kort nozzles and propellers.

We expected to observe significant advantages in changing prop direction, so we chose to model potted-motor thrusters; prop direction can be changed on these thrusters by simply swapping propellers, whereas spiral helical gear thrusters typically are engineered for full-power in only one direction of propeller rotation.

All hull models are full scale, fixed-position, at drilling draft, with a Free Surface in still water. Under-hull models had all six propellers rotating simultaneously.

We used CCM+ CFD software from cd-Adapco (a Siemens company), running on Diamond's 200-core (Ivy Bridge) cluster or on 1000-2000 cores on the Stampede II (Sandy Bridge) cluster at the Texas Advanced Computing Center (TACC) at the University of Texas.

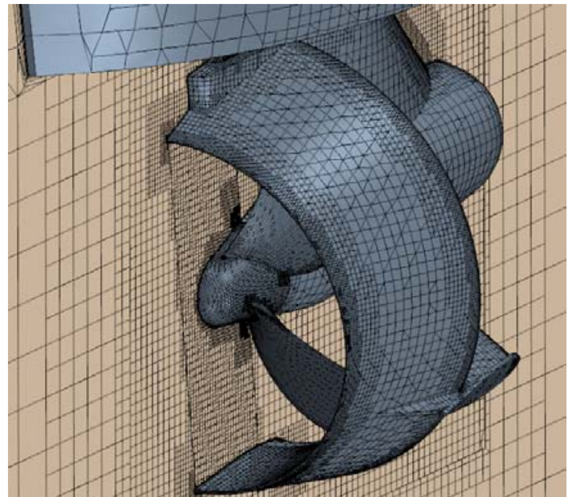

Figure 4: "Trimmer" Mesh in CCM+ on Azipod DZ1400P

All models used a Reynolds Average Navier Stokes (RANS) K-Omega solver, "trimmer" (hexahedral) mesh, and sliding contacts at the propeller-Kort nozzle interface. See Figure 4.

Solver time-step was verified with a time-step convergence study. Generally, unducted propellers can be modelled using a time-step representing 3-4 degrees of prop rotation, but our convergence study found that ducted props require a time step representing no more than 2 degrees of rotation. We measured total thrust force, including the Kort nozzle contribution, not just the prop shaft force.

We modelled three thruster configurations:

(1) Open-Water (thruster suspended at depth on a column; for correlation to manufacturer's thrust data)
(2) Floating Factory drillship, with six thrusters
(3) Gusto P-10,000 drillships with six thrusters

We modelled three propeller rotation configurations (see Figure 5):

(a) **Conventional Thrusters** (CW viewed from astern, "right-hand" rotation)
(b) **Counter-Rotation (A)** (port CW, starboard CCW)
(c) **Counter-Rotation (B)** (port CCW, starboard CW, same as conventional twin screw props)

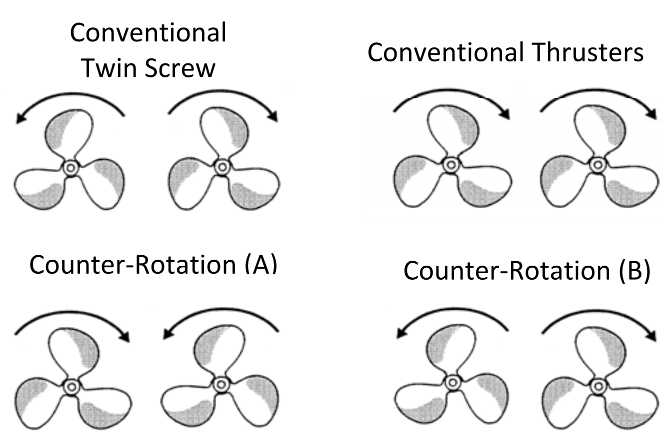


Figure 5: Prop Rotation Configurations, Viewed from Astern

## Drillship Hulls

We modelled the same thruster under two different hulls; the new-design Floating Factory and Diamond Offshore's Blackship drillships (Gusto P-10,000 design).

**Table 2: Hull Comparison, Blackships vs. Floating Factory**

| | Blackship (Gusto P-10000) | Floating Factory |
|---|---|---|
| LWL | 230 Meters | 222 Meters |
| Waterline Beam | 36 Meters | 39 Meters |
| Operating Draft | 11 Meters | 11 Meters |
| Bow | Raked, Fine, With Bow Bulb | Plumb, Full, Bluff Bow |
| Moonpool Leading Edge | "Inverted Wedge" (HHI patent) | Chamfer |
| Moonpool Trailing Edge | Chamfer | Radius |
| Hull Optimization | Unknown (HHI) | MARIN |

Thruster locations for the Blackship drillships are shown in Figure 6; thruster locations for the Floating Factory are similar, except that aft thrusters are substantially in-line close to the stern of the vessel.

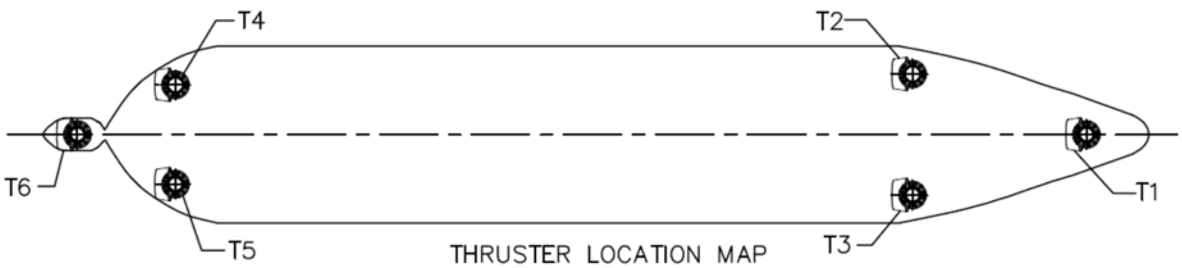


**Figure 6: Diamond Offshore *Blackships* Thruster Configuration**

**Figure 7A: Blackship Hull (Gusto P-10000)**

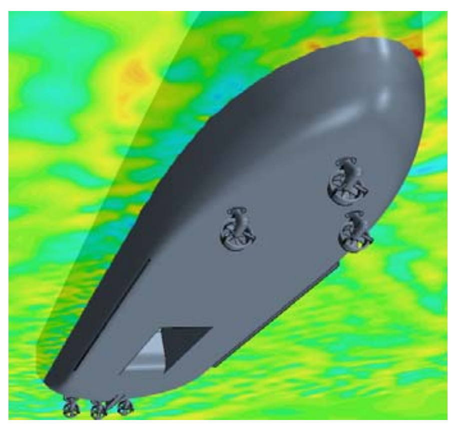

**Figure 7B: Floating Factory Hull**

## Correlation with Open-Water Thrust

We modelled the Open-Water performance of the Azipod DZ1400P thruster at a range of power levels to check the correlation between the CFD model and the manufacturer's open water thrust curve.

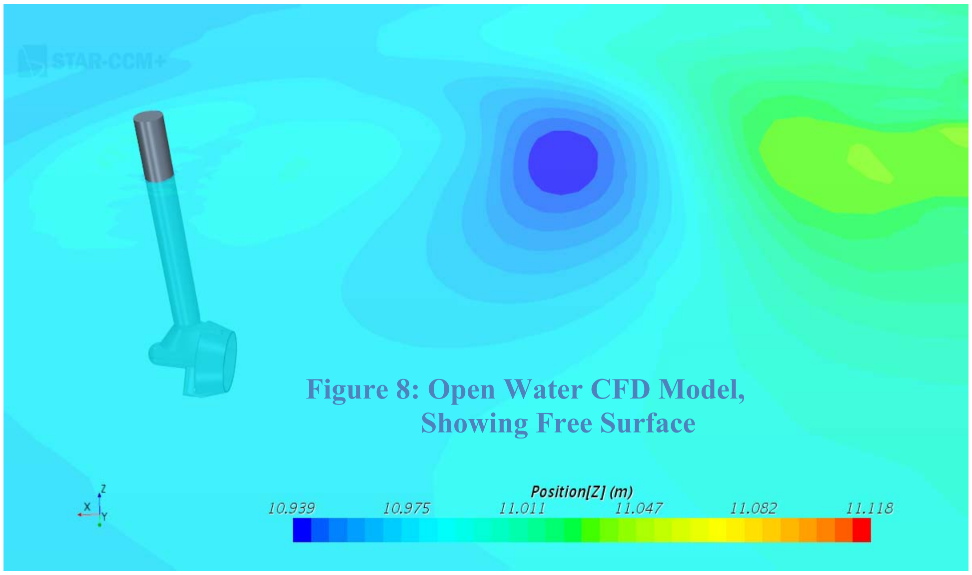


**Figure 8: Open Water CFD Model, Showing Free Surface**

Correlation between manufacturer's data and the CFD model was spot-on:

**Table 3: CFD Correlation to Predicted Open-Water Thrust**

| Percent Input Power | Prop RPM | Thrust Force (Metric Tons) | |
|---|---|---|---|
| | | Mfgr. | CFD |
| 100% | 169 | 105 | 104.99 |
| 80% | 157 | 90 | 90.01 |
| 60% | 142 | 74 | 73.70 |
| 40% | 124 | 57 | 56.88 |

## Under-Hull CFD Models

The Floating Factory and Blackship (Gusto P-10000) hulls were first modelled with Azipod DZ-1400P thrusters at zero degrees heading (dead ahead), and 80% power using *standard* "right-hand" propellers (i.e. all propellers rotating *clockwise* when viewed from the stern), and the thrust compared to the DNV efficiency numbers; see Figure 9.

The Blackship model with Azipods has consistently high thruster efficiencies, while the Floating Factory model with Azipods shows *dips* in efficiency for the starboard thrusters (T3 and T5) and center-aft thruster T6.

The Floating Factory with Azipod results are consistent with the field observations of the Blackships fitted with 7 degree down-angle (geared) thrusters (i.e. lower efficiency on the starboard thrusters, but the Blackships fitted with Azipods are *not*.

Figure 9

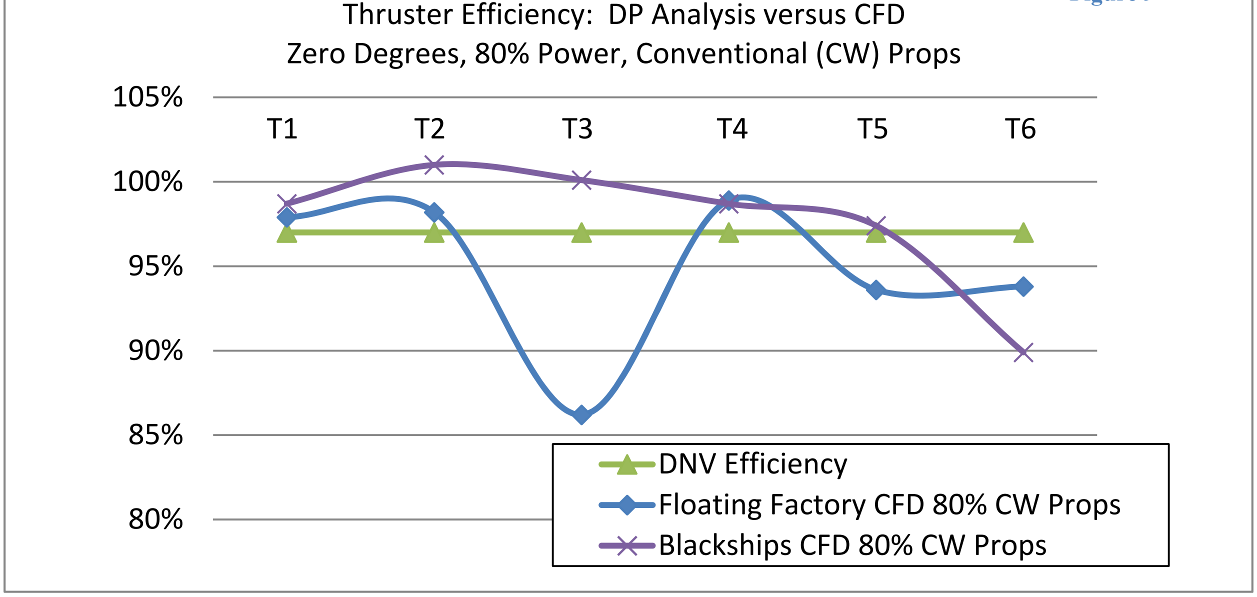


Figure 10

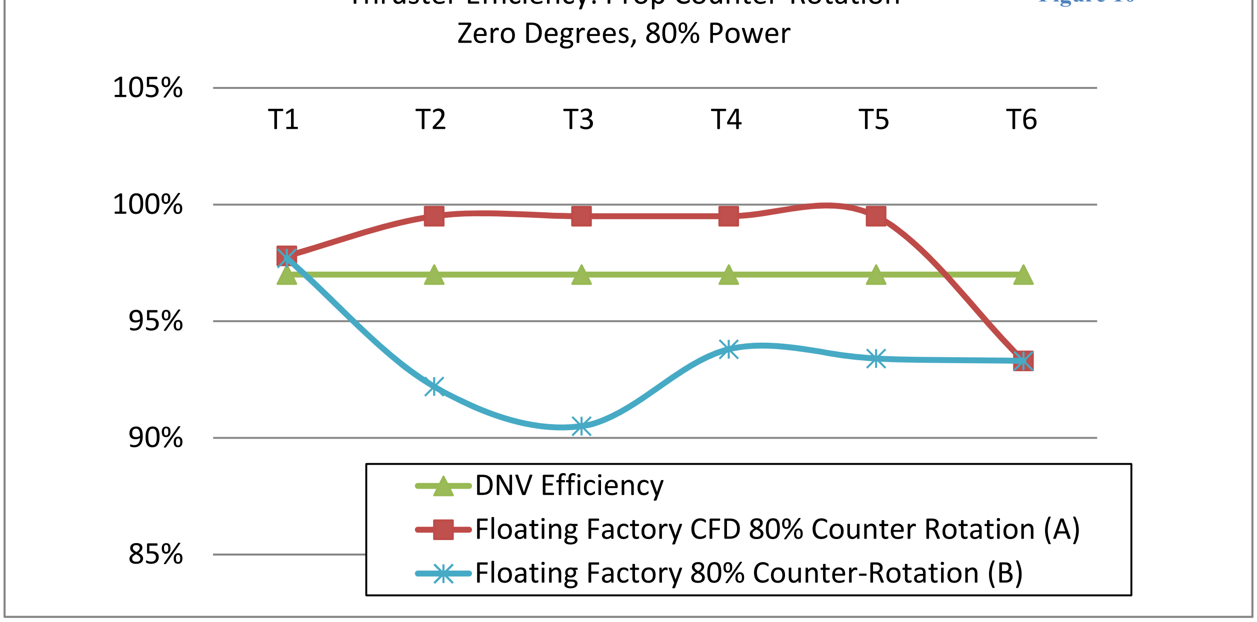


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Figure 10 shows the results of the CFD models of the Floating Factory hull with counter-rotating propellers. Please refer to Figure 5, above for the propeller rotation schemes.

- Counter-Rotation (A) is CW props to port, CCW props to starboard ("together at the top").
- Counter Rotation (B) is the same as conventional twin-screw vessels ("together at the bottom").

Counter-Rotation (A) is clearly a superior scheme; the efficiencies are high, *and* the "mirror-image" thruster pairs (T2 &T3, T4 & T5) performed substantially the same. The only outlier was T6, which consistently showed substantially lower efficiency that the other thrusters.

We theorize that the reduced efficiency of T6 on both the Floating Factory *and* the Blackships hulls is related to the presence of an extended keel skeg on both hull forms. See for example Figure 11.

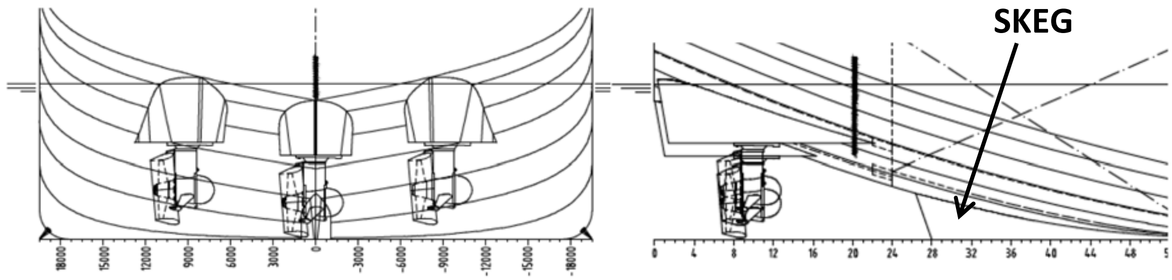


**Figure 11: Floating Factory Aft Lines**

The Floating Factory was further modelled with the same counter-rotating props (A) at various thruster headings, with ***all thrusters at the same heading***, without regard for thruster-thruster interaction.

Headings proceed *counter-clockwise* from zero degrees, such that at 30 degrees, for example, the thruster intake is pointed towards the port forward quarter and the prop wash is pointed at the starboard aft quarter. See Figure 12.

Note that the CFD models at various headings continue to show a smaller but notable dip in efficiency at T6 akin to what was zero degrees heading. This seems to confirm the involvement of the skeg in T6 efficiencies.

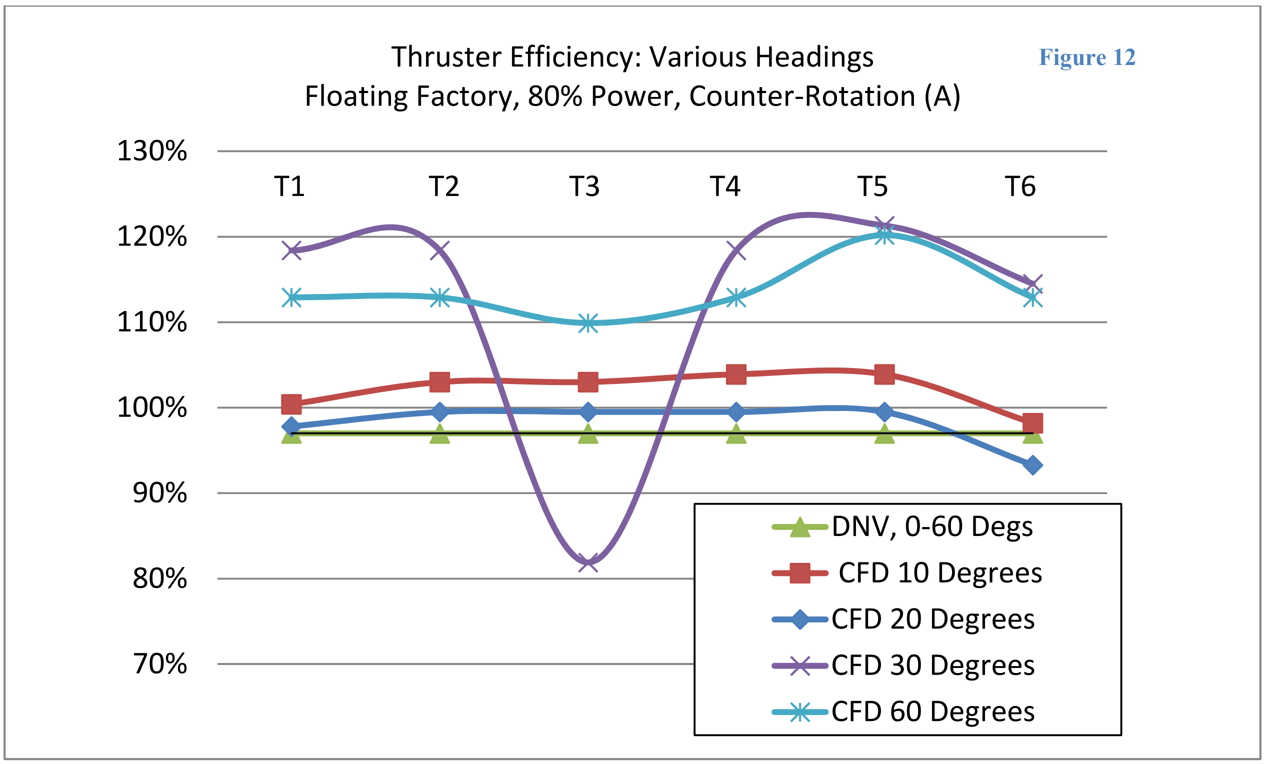


**Figure 12**

Thruster efficiencies gradually increase with heading angles, and reach a peak at 30 degrees heading of about 120% efficiency, before retreating to lower efficiencies at 60 degrees. Further modelling will be required to establish the exact headings for actual peak thrust efficiency for each thruster.

Note that the *dips* in T3 efficiency at 30 degrees and 60 degrees headings are almost certainly due to thruster-thruster interaction between T1 and T3. In bias mode, T3 would typically be an exact mirror-image of T2, so both mirror image thrusters would have the same efficiency at these headings

Figures 13 and 14 (below) show seawater velocity plots of thruster T3 (starboard forward) on the Floating Factory, at 100% input power. In both plots, the 4-bladed propellers are in the same orientation; blades along the vertical and horizontal axes.

Figure 13 shows 30 degree thruster heading, at 117% efficiency relative to Open Water. Figure 14 shows Zero degrees thruster heading, and 99% efficiency.

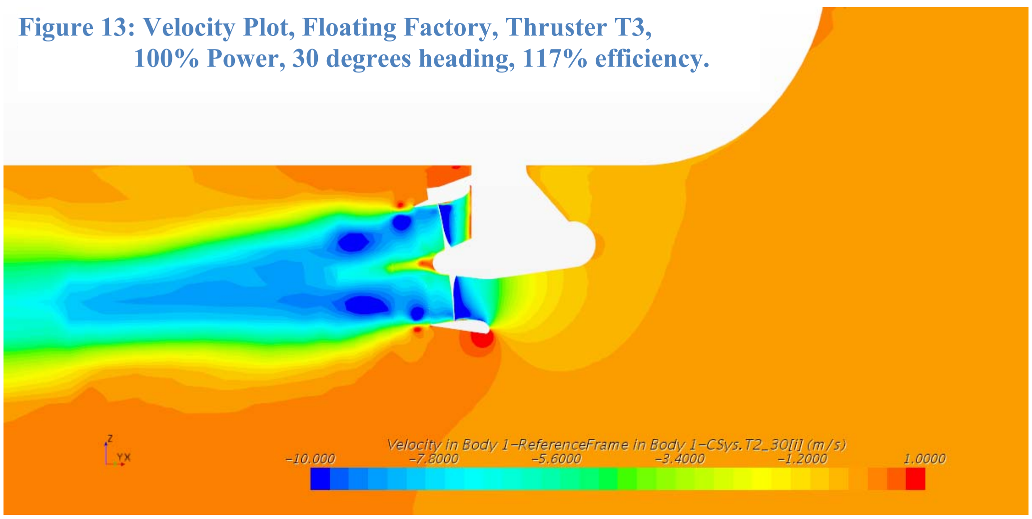


**Figure 13: Velocity Plot, Floating Factory, Thruster T3, 100% Power, 30 degrees heading, 117% efficiency.**

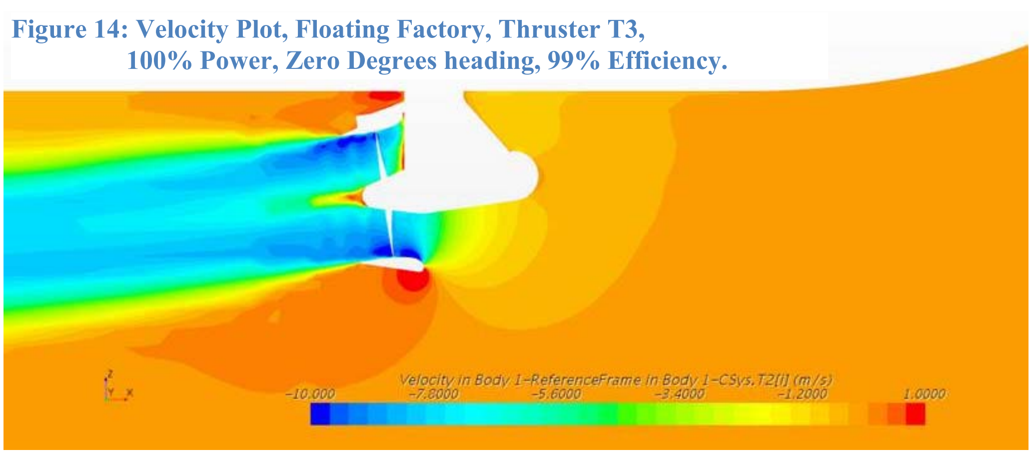


**Figure 14: Velocity Plot, Floating Factory, Thruster T3, 100% Power, Zero Degrees heading, 99% Efficiency.**

Note the tighter prop-wash cone and the increased discharge velocity at 30 degree heading.

The intake velocities do not look substantially different, except that the velocity *gradient* is significantly steeper for the 30 degree heading case.

## Efficiency Improvement, Typical Bias Mode

Figure 15 shows the increase in thruster efficiency demonstrated by the CFD models, relative to the DNV-GL DP analysis, in a typical bias mode arrangement, at 80% power,. The average increase in thruster efficiency in this case is 19.73%.

Across six thrusters, this is equivalent to adding a 7$^{th}$ thruster operating at 118% efficiency.

Figure 15

| Efficiency Increase, Typical Bias Mode, CFD Models vs. DP Analysis 80% Power, Counter-Rotation (A) | | | | | | |
|---|---|---|---|---|---|---|
| Thruster | T1 | T2 | T3 | T4 | T5 | T6 |
| Heading | **0** | **30** | **330** | **150** | **210** | **180** |
| Efficiency Increase | **0.8%** | **21.4%** | **21.4%** | **30.5%** | **30.5%** | **13.8%** |

## Conclusions

- Down-angle azimuthing thrusters have significantly reduced the Coandă Effect on DP vessels, but have simultaneously made thruster efficiency highly dependent upon intake flows.
- Thruster intake flows are dependent upon
  - Thruster position on the hull,
  - Hull shape,
  - Thruster heading, and
  - Propeller direction.

  Previous methods for estimating thruster efficiency do not consider any of these variables.
- We did not model varying thruster positions in this study, as thruster positions were already *fixed* for the vessels in question; that would be a good topic for new DP vessel designs.
- Thruster efficiency did not vary significantly between the two hulls modelled, but hull shape clearly had a strong influence on thruster efficiency, particularly in the stern.
- Thruster efficiency was found to vary significantly with thruster heading, and is generally highest when the thruster heading is substantially normal to the turn of the bilge.
- The most efficient prop direction scheme for the Floating Factory drillship was found to be
  - Right-hand propeller rotation on the port thrusters and
  - Left-hand propeller rotation on the starboard thrusters,

  This is the opposite of the propeller rotation scheme on conventional twin-screw vessels.
- CFD technology is now sufficiently mature that thruster efficiency should be analysed with CFD on a hull-by-hull basis for all new-build DP vessels.

## Acknowledgements

The authors extend special thanks to Dietmar Deter, NAUTEX Inc., for his wise counsel over the last five years on all things "thruster".

## References

(1) Norbert Bulten & Petra Stoltenkamp (2016*). Improved DP-capability with tilted thruster units and smart controls algorithms.* Marine Technology Society. Dynamic Positioning Committee. Dynamic Positioning Conference October 11-12, 2016.