INSIGHTS INTO THE FLOW WITHIN THE WELL DOCK OF A MOTHERSHIP DURING FEEDER VESSEL DOCKING MANOEUVRES

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SUMMARY

An experimental campaign has been undertaken to explore the flow around a feeder vessel as it manoeuvres in and out of the well dock of a mothership. The parent hulls for this study are drawn from the floating harbour transhipper concept created by Sea Transport Corporation. Laser measurement techniques have been employed to analyse the flow field within the well dock while the feeder vessel both enters and departs. For the Master of the feeder vessel to safely perform these manoeuvres, the complex flows resulting from the highly confined nature of the well dock concept need to be understood and potentially mitigated. It is shown that the inclusion of vents in the well dock can significantly influence the flow and that their effectiveness is determined by the size of the vents. This study further progresses the authors' recent work on the same novel concept where the confined water effect of the well dock and inclusion of vents is quantified for both the seakeeping behaviour and the docking/departure performance. It is concluded that the use of vents is very beneficial when a feeder vessel docks or departs the well dock, however a compromise on the vent size must be reached in order to reduce adverse effects on feeder vessel motions when docked and exposed to a seaway. It is likely that the optimum solution, that covers all operational parameters, only requires the inclusion of relatively small vents.

1. INTRODUCTION

1.1 THE FLOATING HARBOUR TRANSHIPPER

The present research focusses on the feasibility of a novel new concept of an offshore cargo holding and handling mothership, the floating harbour transhipper (FHT), to overcome the limitations of traditional side-by-side transhipment and many of the prohibitive characteristics of deep water port development Macfarlane *et al*. (2012). This concept introduces a well dock in the aft end of the mothership in which a feeder vessel docks during cargo transfer. Here it will be sheltered from the incident sea state, significantly widening the weather window for transhipment. The concept can be observed in Figure 1 which shows the scale models of the FHT, Cape Size ocean going export vessel and the proposed feeder vessel docked in the aft well dock of the FHT. There are many operational advantages of the well dock concept, with the primary aim to transfer more cargo to an ocean going vessel at higher rates and in larger sea states than traditional transhipping operations. The application of well docks to transhipment in the specific context of the FHT has been previously discussed by Ballantyne *et al*. (2012), Macfarlane *et al*. (2012, 2015a, 2015b) and Johnson (2018).

The inclusion of the well dock leads to two interesting design criteria in terms of successful transhipment operations. The feeder vessel needs to first enter the well dock and then be unloaded (or loaded) once docked, in maximum sea states higher than traditional transhipment methods to provide superior throughput compared to traditional transhipment methods. Understanding the docking and seakeeping behaviours of the two vessels is paramount to the successful implementation of the well dock to improve transhipment operations. Once the feeder vessel begins to enter the well dock, the challenges of manoeuvring within a very narrow and shallow channel must be overcome, including well-known confined water effects.

Figure 1: Photograph of the three physical scale models showing the general arrangement of the FHT system. The black hulled ocean going vessel (OGV) is nearest the camera, the green hulled FHT is behind the OGV and the bow of the feeder vessel (navy blue hull) can be seen protruding from the stern well dock of the FHT (left).

The confined water scenario within the well dock is analogous to a vessel operating in locks as these operations often involve very limited lateral and under keel clearance. Ship behaviour in locks was the focus of the 3rd International Conference on Ship Manoeuvring in Shallow and Confined Water and this provided a wealth of published literature on the topic (Vantorre *et al*., 2013). CFD simulations have since been undertaken by Toxopeus and Bhawsinka (2016) to investigate the hydrodynamic interaction forces on a large-beam vessel entering the Pierre Vandamme Lock. This work was validated by comparing the lateral and longitudinal forces against the captive model test results published for benchmarking purposes by Vantorre *et al*. (2012) and Vantorre and Delefortrie (2013). These physical captive tests were performed using a 1/75 scale model of a 265 m L_{OA} bulk carrier with a beam of 43 m entering a lock that is 57 m at a speeds between 1.5 and 2.0 knots full scale. These speeds are similar to the docking speeds proposed for the feeder vessel as it enters the well dock. Even though the feeder vessel will be much smaller than the bulk carrier tested by Vantorre *et al*. and has different lateral and under keel clearance characteristics, the blockage ratio will be similar. In addition to force data that Toxopeus and Bhawsinka (2016) used to validate their model, they presented velocity fields around the vessel which give an insight into the flow fields expected within the lock.

However, further complexities arise from the fact that the well dock is an enclosed space, thus a large volume of water must escape the well dock as the feeder vessel enters (equivalent to the volume of water that the feeder vessel displaces, which in the case of the FHT is a considerable percentage of the total volume). The reverse is then the case when the feeder vessel departs – a large volume of water must enter the well dock. The significance of the constriction posed by the mothership well dock is depicted in Figure 2. Regardless of whether the feeder vessel enters or exits the well dock, the volume of water must pass through this constricted space between the feeder vessel and well dock floor and side walls. Clearly, the velocity of the water flow will be significantly greater than, and predominantly in the opposite direction to, the feeder vessel speed - posing further challenges given the propulsors must operate in this complicated environment.

The resultant changes in pressure will in turn affect the bodily sinkage and trim of the feeder vessel and the force required to move it. Recognising these issues and subsequent challenges to safe and controlled manoeuvring, consideration was given to the inclusion of some strategically located vents in the well dock, these allow water to exit/enter the well dock by other means than the well dock entrance, thus mitigating the adverse/unknown effects.

Much of the published literature on the topic of well docks is related to their application to military amphibious vessels as in the work of Cartwright *et al*. (2006, 2007) and Bass *et al*. (2004). The proposed venting for the FHT concept demonstrates a significant departure from the well dock geometry of amphibious vessels. The study of a (feeder) vessel operating in such a confined well dock, plus the inclusion of such vents, is unavailable in published literature. The unique hydrodynamics that occur within this scenario, including the effect of these vents, is a focal point of the current research. Given the distinctively novel application, much of the research performed and reported here has required an approach predominantly based on physical scale model experimentation. Early attempts to simulate the complex hydrodynamics using a numerical approach highlighted the essential need to validate against relevant experimental data, which was not found in the public domain.

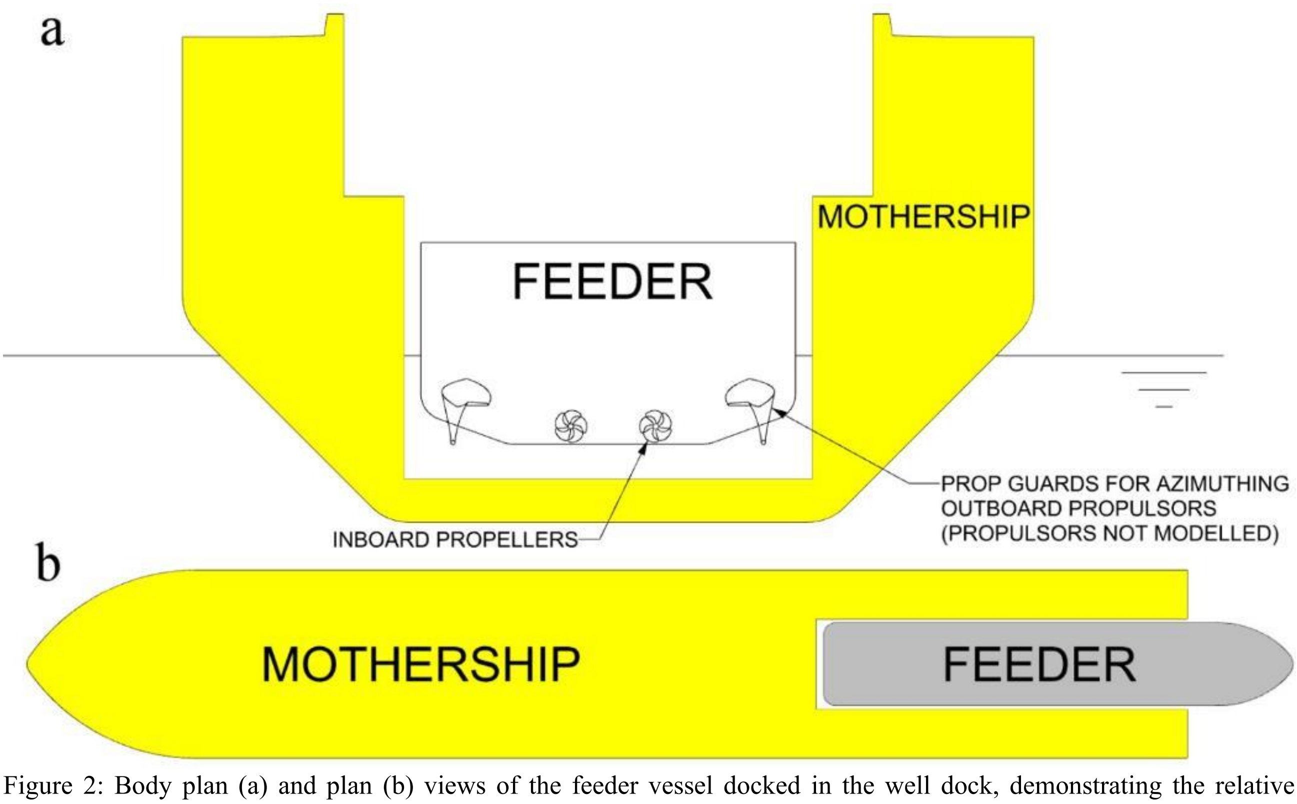

Figure 2: Body plan (a) and plan (b) views of the feeder vessel docked in the well dock, demonstrating the relative difference between the feeder vessel and well dock cross sections for the present study. The location of the propulsors and prop guards are also highlighted.

1.2 VENTILATED WELL DOCKS FOR TRANSHIPMENT

The current research explores the merits of applying the well dock concept to transhipment operations and some associated challenges have been identified. To build confidence in such a novel re-imagination of well-established transhipment processes (involving side-by-side mooring of ships) these challenges require further investigation. Many of the benefits of well dock transhipment come from the improved seakeeping performance of the feeder vessel when docked within the well dock. In particular, the vastly improved relative motion between the two vessels leads to a wider weather window for materials transfer (Macfarlane *et al*., 2012).

The challenges posed by implementing the well dock are primarily due to the unique confined water scenario that results when the feeder vessel enters the finite volume of the well dock. To put this into context, once fully docked, approximately 55% of the total water contained within the well dock must be displaced.

Earlier phases of this research have found that the limited under keel clearance between the well dock floor and the keel of the feeder vessel when it is docked means that the relative motions between the two vessels is very important due to the potential for undesirable contact. The limited under keel clearance is partially mitigated by the sheltering effect that the mothership provides for the feeder vessel. The sheltering effect was found to reduce feeder vessel motion and thus reduce relative motion between vessels. The confined water scenario would likely lead to challenges in docking the feeder vessel within the well dock. To mitigate these confined water effects it was proposed that a pair of vents be included in the well dock side walls at the forward end. The intent of these vents was to allow water to exit (or enter) the well dock without needing to flow past the entering feeder vessel, reducing confined water induced trim and sinkage effects. This would subsequently reduce the likelihood of contact between vessels.

The effect of these well dock vents on the seakeeping behaviour has been explored by measuring the motions of the two vessels individually and combining the effects to track the minimum under keel clearance. With the feeder vessel docked stern-first in the well dock of the mothership, the two vessels were moored with the mothership exposed to regular head seas. The feeder vessel was in its fully laden load condition and the mothership in a configuration representative of the lightest condition that allowed the feeder vessel to enter the well dock. This modelled a realistic operational worst case for the seakeeping performance because both the under keel clearance between the vessels and the displacement of the mothership were at a minimum. A series of four vent configurations were tested to develop an understanding of the effect of the vent size on the seakeeping performance of each vessel; vents 100% open, vents 50% open, vents 25% open and no vents. It was concluded that adding vents to the well dock had negligible effect on the motions of the mothership itself. However, the vertical motions of the docked feeder vessel increased, particularly when the vents were fully open. The most favourable configuration was when there were no well dock vents, followed by the vents 25% open configuration. The main driver for the inclusion of well dock vents is the docking and departure performance and this requires further investigation to understand the effectiveness of vents in well docks.

This aspect of the concept has been investigated by performing a similar series of experiments surrounding the performance when docking the feeder vessel. To reduce the level of complexity and number of variables this initial study was limited to calm water conditions. The load conditions for both vessels were chosen to represent the worst operational case in terms of under keel clearance. However, in this case the mothership was rigidly fixed to the basin floor such that it was restricted from all motion. The feeder vessel was towed both into and out of the well dock via parallel rails allowing the sinkage, trim and longitudinal force to be measured. One of the primary purposes of this investigation was to determine the effect that the well dock, and each of the vent configurations, have on the docking and departure performance of the feeder vessel. The same four vent configurations were investigated, each over a range of feeder vessel entry/exit speeds from one to three knots full scale. It was concluded that the vents had a significant effect during the departure manoeuvre and the effect was speed dependant.

There were several interesting phenomena observed while investigating the docking manoeuvre. The inclusion of vents yielded less longitudinal force on the feeder vessel but had little effect on the trim and sinkage behaviour. It was identified that the finite length of the well dock had a significant effect on the feeder vessel that was most visible during the docking operation where it caused a bow down trim and a bodily rise. This behaviour was found to be contrary to the traditional confined water motion response. This was hypothesised to be caused by the propagation of energy ahead of the feeder vessel that is not able to escape the well dock, potentially due to the fluid flow transitioning into the trans-critical regime as defined by Tuck and Taylor (1970).

Possible reasons for the confined water behaviour exhibited by the feeder vessel when docking or departing the well dock have been hypothesised, however the type of data acquired, namely vertical motions and longitudinal forces, was inadequate to conclusively prove these hypotheses to be true. The current stage of the project, reported in this paper, is focussed on utilising flow visualisation techniques to further support these findings. The method adopted was particle imaging velocimetry (PIV) using a LaVison sCMOS 5-megapixel camera for image capture and a pulsed laser sheet to illuminate fluorescent particles in the plane of interest. Two images are captured with a very short and precisely controlled interframe time which allows the path of the fluorescent particles to be tracked through time. PIV has a wide variety of applications and there is ongoing active research developing this measurement technique for new applications to enable increased measurement precision of increasingly complicated flow fields. PIV has been adopted to capture detailed maritime hydrodynamic flow field properties in or around structures and objects including ocean wave energy converter devices (Fleming *et al*., 2017) and vessel control and lifting foils (Ashworth Briggs *et al*., 2014).

This project applies a widely validated 2D PIV technique to this novel application to capture the complex flow within the well dock and to visualise the variations that occur between the selected vent configurations. The scope of these initial experiments cover a practical range of vessel speeds and flow restrictions, which lead to a wide range of expected flow conditions. The primary objective from this study is to compare the flow within the well dock between the four vent configurations when the feeder vessel enters and exits the well dock of the mothership. A detailed study is warranted to confirm the need for vents and their size due to the significant impact on the structural design of the mothership and controllability of the feeder vessel.

1.3 FLOW VISUALISATION IN CONFINED WATERWAYS

Flow visualisation techniques are often employed to allow researchers to observe the fluid flow within a domain of interest and can be used to better explain a measurement or trend that is contrary to what is expected. Flow visualisation experiments or simulations are also often performed when the researcher has limited knowledge on what to expect from a given scenario. With the increased accessibility and measurement abilities of non-contact flow visualisation techniques during modern times, such techniques are now adopted as a primary data source. For example, Jurgens *et al*. (2006) applied PIV techniques to visualise the flow around a scale model of a 300m LNG carrier operating in confined water in the MARIN shallow water test basin. The data obtained contributed to a better understanding of shallow water effects on the prediction of the hydrodynamic derivatives, and accelerated the development and validation of numerical prediction methods such as potential flow, RANS and semi-empirical simulation codes. The authors concluded that the flow characteristics were very promising for future CFD validation and that the PIV measurement system was found to be very robust and reliable, even in very shallow water conditions. There are several procedural handbooks and benchmark investigations available to assist facilities to introduce PIV measurement capabilities into their repertoire. Three such examples include a very application-focussed guide by Raffel *et al*. (2013); the PIV benchmark tests as published by Muthanna *et al*. (2010) and the International Towing Tank Conference (ITTC) guidelines for both 2D and 3D PIV benchmark tests and data repository (Fu *et al*., 2017).

2. EXPERIMENTS

An experimental program was undertaken using two-dimensional PIV to measure and visualise the fluid flow within the well dock during feeder vessel manoeuvres. The flow was captured for both the inbound (feeder vessel docking) and outbound (feeder vessel departing) manoeuvres to investigate the effect that various well dock ventilation conditions has on the flow field.

The experimental program was undertaken at the Australian Maritime College (AMC) utilising the 35 m long by 12 m wide finite depth wave basin using a process very similar to earlier tests to ensure consistency. Slight modifications were made to the experimental apparatus to enable flow visualisation techniques to be incorporated. Calm water docking tests were conducted whereby the feeder vessel model was towed using a carriage mounted on two parallel rails which enabled the model to be towed in a controlled manner with precise and consistent location, acceleration and velocity profiles. The feeder vessel started a docking (inbound) run and ended a departure (outbound) run at a position approximately four feeder vessel lengths away from the docked position. The docked position was set to be 35mm (2100mm full scale) between the transom of the feeder vessel and the end wall of the well dock (see Figure 3). The acceleration and deceleration rate of the feeder vessel was consistent and linear for all runs. This consistency in both the docked position and the ramp rates allowed the flow within the well dock to be interrogated at a very reliable and consistent position that was the same for each speed in both directions. This ensured that any variation observed between speeds or vent configuration was a product of the independent variable rather than analysing a slightly different portion of the position domain data.

For these experiments the mothership model was substituted for a purpose-built apparatus that accurately represented the well dock and vents (when appropriate) while providing dry regions for the camera, laser sheet optics and mirrors required for capturing the PIV images. The internal shape of the well dock remained identical to the mothership model but only the internal faces of the well dock and vents were modelled as shown in Figure 3. The well dock and vent model was constructed primarily using Perspex to allow visibility through the floor of the well dock for the camera and the transmission of the laser sheet through the walls of the well dock.

A sunken pit below the concrete floor of the basin was sealed from the ingress of water for this experiment and used to position three mirrors to redirect the view of the camera and one to redirect the path of the laser sheet. These mirrors enabled the camera and laser to be positioned above the water surface removing any requirements for waterproof housings or borescopes and simplifying the optical considerations. A simplified representation of the transom of the mothership was adopted. Comparison with previous experiments showed that this simplification had no measurable effect upon the docking performance of the feeder vessel. The vent opening configuration was altered by means of interchangeable blocks that altered the length of the vent opening as demonstrated in Figure 4.

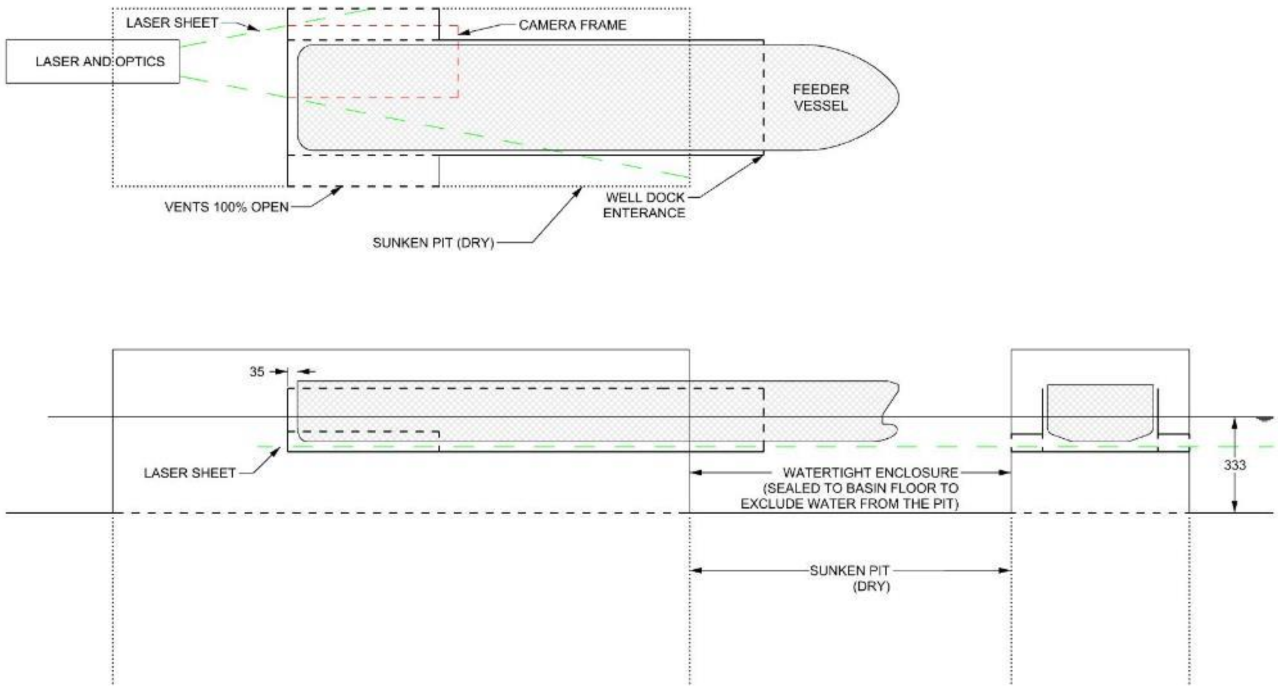

Figure 3: Experimental apparatus positioned over the sunken pit showing the feeder vessel in its docked position showing the location of key PIV equipment.

Figure 4: Profile view of the well dock (full length) illustrating three of the vent configurations, 100% open (all shaded areas), 50% open (two darker shaded areas) and 25% open (the darkest shaded section). Note: vents were present on both sides of the mothership well dock.

The principal particulars for the feeder vessel and the simplified well dock model are outlined in Table 1. The vessel conditions are considered to represent a realistic worst case scenario, with the feeder vessel at full load displacement (this is intended to be the scenario for every case during normal operations) and the mothership at a light load condition. This combination presents the minimum practical under keel clearance between the keel of the feeder vessel and floor of the well dock

As the feeder vessel docks it must displace approximately 10,000 tonnes of water from the well dock (full scale), which represents approximately 55% of the total volume of the well dock. The width of the well dock is 109% of the feeder vessel beam; the length of the well dock is 79% of the feeder vessel length (the entirety of the feeder vessel is not intended to fit within the well dock, just the cargo-carrying portion). The static water depth to draught ratio within the well dock is 1.4. A photograph of the feeder vessel model docked within the well dock is presented in Figure 5 showing the Perspex well dock model terminating between the two AMC stickers on the feeder vessel. The inboard propulsors and outboard prop guards were included on the scale model of the feeder vessel (refer Figure 2). The azimuthing outboard propulsors were not modelled due to the complexity of this system.

Table 1: Principal particulars of the tested experimental vessel conditions.

	Simplified Well Dock		**Feeder Vessel**	
	Ship	**Model**	**Ship**	**Model**
LOA [m]	99.00	1.650	125.00	2.083
Beam [m]	24.00	0.400	22.00	0.367
Draught @ LCF [m]			5.19	0.087
Depth in well dock [m]	7.26	0.121		
Displacement [t]			11284	0.051
Trim [degrees]	0	0	0	0
VCG [m]			9.35	0.156
LCG (from transom) [m]			57.81	0.964

The aims of the experiment required as much consistency between comparative conditions as possible and as a result the feeder vessel speed profile was precisely controlled. The three steady-state test speeds of 1.0, 1.5 and 2.0 knots full scale were used in both directions for each vent configuration. These speeds were selected as they were considered by the Master Mariners consulted as being realistic for these somewhat unique docking and departure operations. A constant and equal linear ramp rate was applied to all acceleration and deceleration events which resulted in acceleration to the highest steady-state test speed of 2.0 knots in approximately 58% of the well dock length. Whenever reference is made to feeder vessel speed in this paper it refers to these nominal full scale steady-state speeds of 1.0, 1.5 or 2.0 knots. However, all flow velocity values remain in model scale as the scale effects associated with a confined flow such as this make transferring these results to full scale impractical at this early stage of investigation. The topic of scale effects on flow fields around vessel in confined waters was touched on by Haase *et al*. (2017) if the reader is seeking further detail on scaling flow velocity measurements.

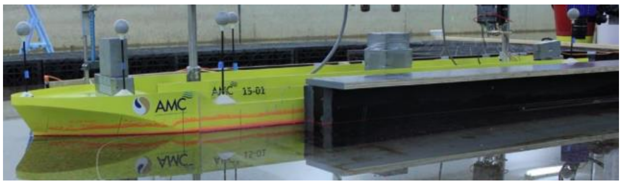

Figure 5: Photograph of feeder vessel model docked within the Perspex well dock model. The fluorescing wax particles can be seen accumulating along the feeder vessel near the waterline and a second line slightly higher where the vessel has been heeled over during setup.

Repeat runs were included across the range of speeds and vent configurations (one speed per configuration was repeated at least twice) to improve data integrity and results were compared to preliminary flow visualisation tests using dye injection for verification purposes. Flow velocity measurements were also checked against preliminary hydraulic approximation calculations for the no vents configuration to develop confidence in the measurements. The measured flow speeds also correlated well with the work of Toxopeus and Bhawsinka (2016) whom performed simulations at similar speeds with a similar blockage ratio.

The water inside the well dock was seeded with custom-made neutrally buoyant fluorescing wax particles each time the feeder vessel was out of the well dock (every two runs) to maintain adequate and consistent seeding. The particles had an approximate size range of 30 – 100 microns and were premixed in a container (~10 litre capacity) prior to being introduced into the test volume to achieve an acceptable seeding density.

The feeder vessel model was free to roll, pitch and heave while being constrained in surge, sway and yaw. PIV images were captured for the entire duration of each run; from a completely stationary condition, the entire period that the feeder vessel was moving through the well dock and for a period following this movement to capture all relevant stages of water flow. Four vent configurations were investigated; vents 100% open, vents 50% open, vents 25% open and no vents; and for each vent configuration the docking and departure manoeuvres were performed at each of the three nominated feeder vessel speeds. The primary measurements for this experiment were the PIV images to visualise and quantify the flow within the well dock. The plane on which the flow was measured was one quarter of the well dock vent height above the well dock floor. This is midway between the underside of the feeder vessel keel and the well dock floor when the feeder vessel is docked and stationary. This position is expected to give a good indication of the dominant influences on the flow field and provides a good foundation on which to build an understanding of the flow within the well dock. The camera frame covered half of the width of the well dock (it was assumed the geometric symmetry of the experiment would result in symmetrical results about the centreline) and extended from the end wall of the well dock to a small distance aft of the largest vent opening as shown in Figure 3.

Other data sets were recorded to ensure consistency with previous investigations, including the heave motion, pitch motion and longitudinal force experienced by the feeder vessel. The speed of the feeder vessel model was recorded using the speed control unit linked to the electric drive motor. Feeder vessel position was also monitored using a Qualisys digital video motion capture system covering the full range of motion as well as a linear displacement sensor with a range of 1.5 m for the transit through the well dock where the precise position was desired.

3. RESULTS AND DISCUSSION

Image processing techniques were used to analyse and quantify the flow field within the well dock. A single and consistent feeder vessel position (where the vessel was at the steady-state speed) was analysed from each scenario to ensure that any variation in the observed flow field was due to either the approach speed or the vent configuration. Sensitivity studies were performed on the image processing parameters to ensure the highest level of accuracy. Once selected, the image processing parameters remained consistent for all analysis. No data smoothing or filling was performed as this was deemed unnecessary for this application and could mask some features of the flow field. The flow field for each run and the four vent configurations were compared for both the docking and departure manoeuvres. The plane on which the flow field is presented is halfway between the underside of the feeder vessel and the well dock floor and in all flow field images the feeder vessel outline has been superimposed to demonstrate its position within the well dock.

The first series of results presented and discussed (Figures 6 to 11) are taken at the point in time when the feeder vessel is 70% docked (NB: 100% indicates the feeder vessel is in the fully docked position, as described in Section 2, while 0% is when the transoms of the feeder vessel and mothership are level). The docking case, where the feeder vessel enters the well dock stern first, is presented in Figures 6,7 and 8 (1.0, 1.5 and 2.0 knots respectively). Similarly, the results for the departure case (exits bow first) are presented in Figures 9, 10 and 11.

Figure 6 shows the flow field for each of the four vent configurations when the feeder vessel docks at the slowest speed of 1.0 knots. There is a stark contrast in the results for the three cases that include vents compared to the sole case where there are no vents. Interestingly, there are significant similarities between the three cases with vents, with a gradual reduction in flow velocities close to the vent as vent size increases. This is expected given the increased area for water to escape the well dock. It is interesting to note that the only flow of measurable significance within the no vents configuration was confined to the region immediately beneath the feeder vessel where there is an approximately even outward flow across the full width of the well dock. For the vents 25% open case the water particles in this same region were all but stationary indicating that the bulk of the water escaping the well dock was now flowing through the open vent, as intended. The vents 50% and 100% open configurations show reduced flow velocities through the vent but also a low velocity flow moving inwards (with the feeder vessel) through the well dock entrance which increases with increased vent opening. This inward flow is consistent with the viscous effects surrounding the feeder vessel and indicates that the PIV plane could be passing through the boundary layer of the feeder vessel. There is a region in the centre of the well dock near the end wall that exhibits nearly zero flow velocity across all vent configurations. The area of this region was smallest for the vents 25% open configuration and grew with increased vent opening. This region is most likely stagnant due to its location within the well dock and the symmetrical nature of the flow field.

Figure 7 presents the flow field comparison for each of the four vent configurations for the slightly faster docking approach speed of 1.5 knots, which shows strong similarities to the results for the 1.0 knots approach speed. The primary difference to the slower approach speed is that the observed flow speeds have increased for all vent configurations and the flow is slightly more consistent. Again, the flow direction beneath the feeder vessel is outward for the no vents configuration, negligible for the vents 25% open configuration and inward for the vents 50% and 100% open configurations. The flow velocity through the vent again decreased with increased vent opening and the region of near zero flow at the centre of the end of the well dock was consistent with the 1.0 knots approach speed condition.

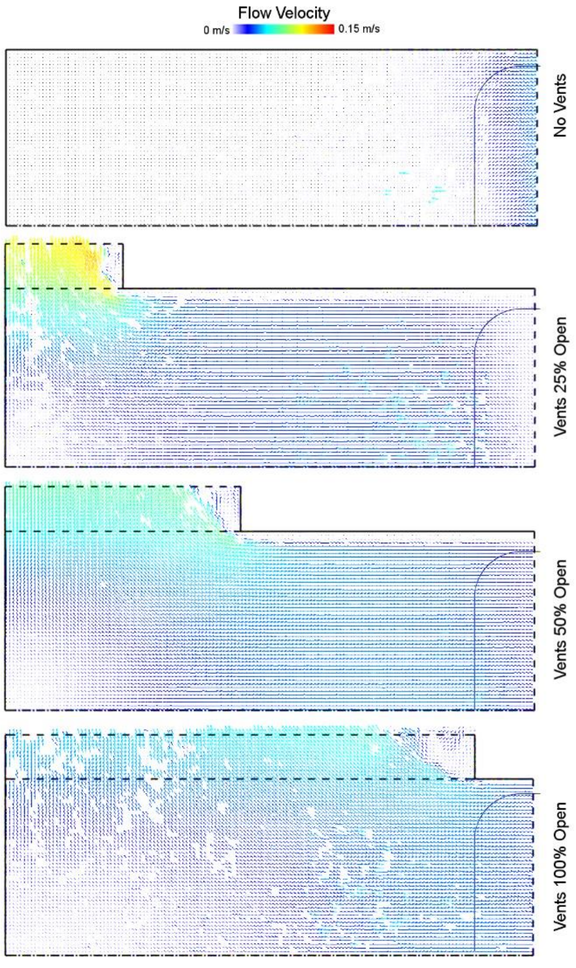

Figure 6: Flow visualisation for the feeder vessel docking across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

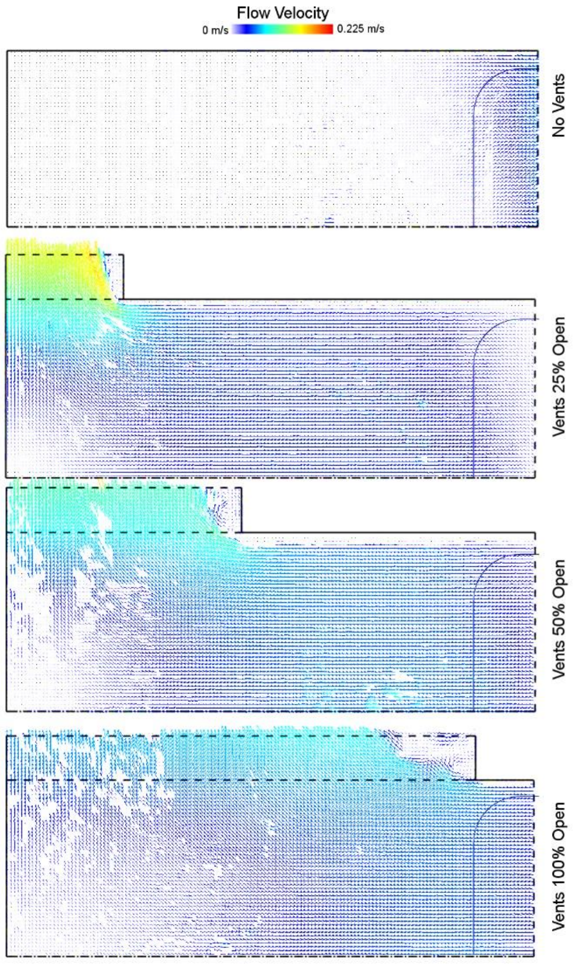

Figure 7: Flow visualisation for the feeder vessel docking across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.5 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

Similarly, Flow visualisation for the 2.0 knots approach speed is presented in Figure 8. This shows very comparable trends to the 1.0 and 1.5 knots docking speeds. Flow speeds again increase proportionally to the docking approach speed and the 25% open vent causes very little flow to occur through the well dock entrance. As the vent size is increased further, water begins to enter the well dock through the entrance and gains velocity with increased vent size.

The same process was undertaken for the outbound departure manoeuvre (for the same three speeds) with the flow analysed at the same longitudinal location as for the docking manoeuvre using the same image processing parameters. While there was no significant change in flow field trends within the well dock across the three vessel speeds during the docking manoeuvre, this was not the case for the departure manoeuvre. It was also found that more care and effort was required to maintain adequate seeding within the region of interest, as less densely seeded water was drawn into the well dock through the vents during the outbound runs. This yielded flow field measurements that occasionally appear patchy due to areas of lower particle density. This was found to be most problematic for the vents 50% open condition.

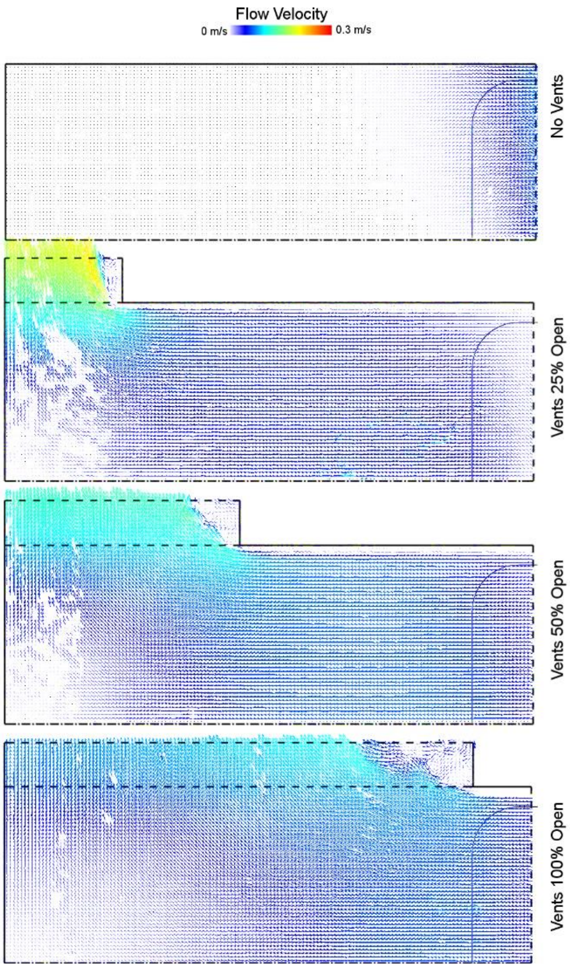

Figure 8: Flow visualisation for the feeder vessel docking across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 2.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

Figure 9 presents the flow field within the well dock for each of the four vent configurations for the 1.0 knots steady-state departure speed. The no vents configuration yields a large region of negligible velocity at the innermost end of the well dock. A strong and reasonably linear inflow was observed on the outside quarter of the well dock width along with a confused flow that trends inwards in the centre half of the well dock. These regions indicate that fluid is flowing around and beneath the feeder vessel to fill the void created by its departure, but this inflow is interacting with the boundary layer of the feeder vessel close to its centreline where the under keel clearance between the two vessels is smallest.

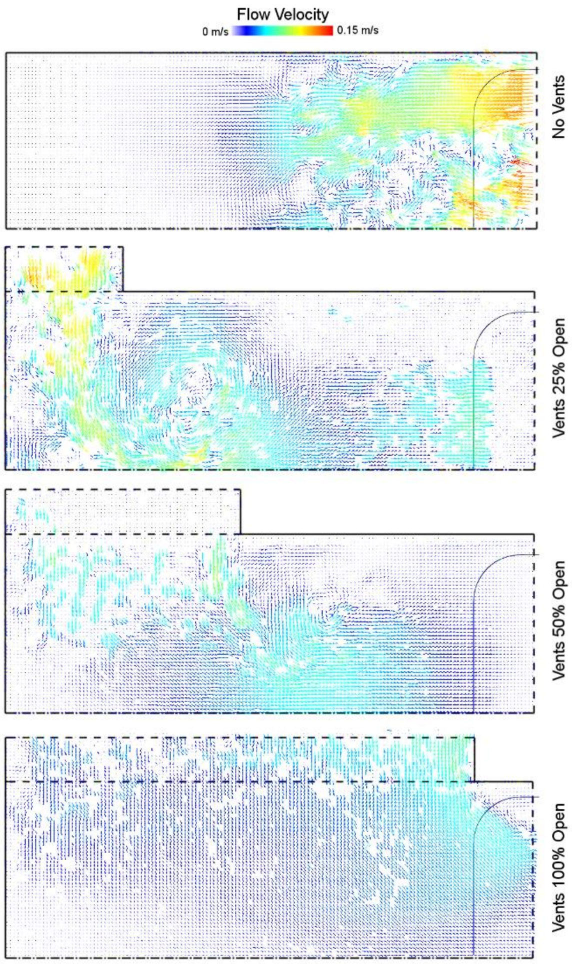

Figure 9: Flow visualisation for the feeder vessel departing across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

For the vents 25% open configuration, a region of almost stationary flow is observed beneath the stern of the feeder vessel in a similar manner to the corresponding configuration during the docking manoeuvre. The flow entering the well dock through the vent appears to have significant momentum, demonstrated by the fluid vectors remaining perpendicular to the feeder vessel motion before interacting with the flow from the opposite side vent. This causes the water entering from each vent to swirl before following the feeder vessel as it departs through the well dock entrance. There is a small region of circulating flow present in the outside quarter of the well dock just in front of the vent as most of the flow towards the entrance is through the centre half of the well dock indicating that the inertial properties of the fluid play a significant role in the measured flow. When the vent size is increased to 50% open the peak velocity of the flow through the vent decreases and the flow across the vent becomes more even. The vortex observed due to the fluid momentum becomes less pronounced and moves aft and slightly outwards. Further widening of the vents to 100% open yields a flow pattern that is more uniform and very similar, but reversed, to the flow pattern that is observed when the feeder vessel is docking for the corresponding vent case.

When the steady-state departure speed is increased to 1.5 knots (see Figure 10) there are significant similarities with the behaviour observed for the 1.0 knots departure case. As for the inbound direction, the no vents condition yields a slightly more consistent flow at 1.5 knots. This trend continued for the vents 25% open condition where the increased flow velocity leads to greater definition of the vortex. When the vents are 50% open, the flow field displays a slightly stronger longitudinal flow pattern, but the flow pattern continues to look very similar to the corresponding configuration at 1.0 knots. A similar result is also found once the vents are fully open.

The flow field results for the highest departure speed investigated are presented in Figure 11. Not surprisingly, the complex flows observed at the slower speeds for the no vent and 25% open vent cases are even more pronounced at 2.0 knots due to the increased velocities involved. The flow behaviour is more consistent, particularly for the no vents condition. The vortices observed in the 25% and 50% open vent conditions were found to be not as tight as the slower speed equivalents due to the increased fluid momentum.

Up to this point, only the fluid flow pattern at a single moment in time (feeder vessel position) during the docking and departure manoeuvres has been investigated. This approach was adopted to isolate the effect of the vent opening on the flow field within the well dock during feeder vessel manoeuvres. These results demonstrate significant differences between the no vent and the open vent conditions (particularly 25%). The logical extension is to expand the investigation from a single (common) feeder vessel position to several longitudinal positions (time-steps) along the length of the well dock. To investigate the flow development behaviour, a series of four snapshots are interrogated over the period of the feeder vessel moving through the camera frame. The four feeder vessel positions investigated are 93%, 84%, 75% and 66% docked. Although all three feeder vessel speeds and four vent configurations were investigated for each of the docking and departure cases, only a select few cases are presented here to demonstrate flow development behaviour during the feeder vessel manoeuvres. The no vent and vents 25% open configurations at the single steady-state docking/departure speed of 1.0 knots were selected due to the stark differences observed between them in the preceding analyses (Figures 6 and 9).

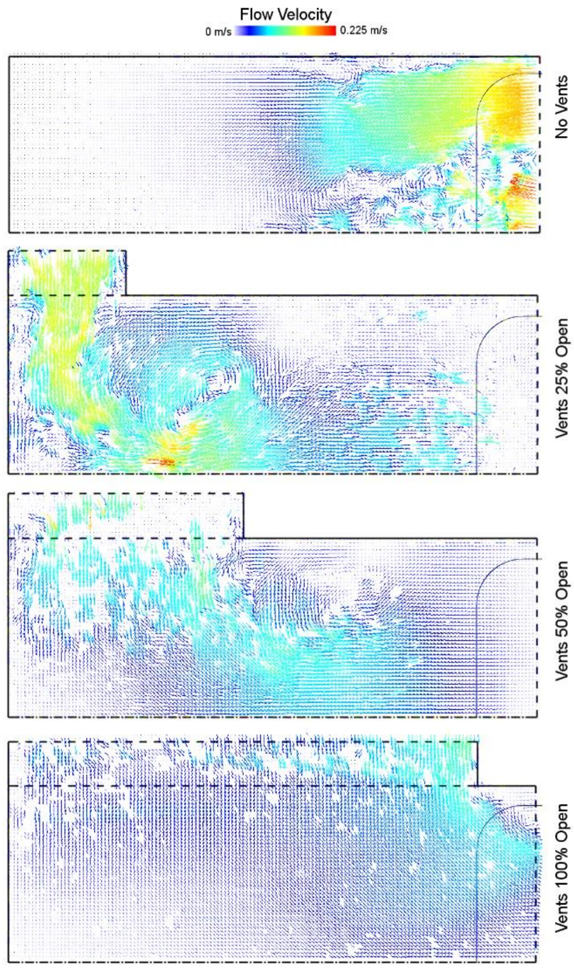

Figure 10: Flow visualisation for the feeder vessel departing across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 1.5 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

The flow development for the feeder vessel docking at 1.0 knots into a well dock with no vents is shown in Figure 12. At a feeder vessel position of 66% docked there is almost zero flow recorded within the capture frame, but as it moves further into frame (at a position of 75% docked) there is a very even outflow under the vessel, beginning close to the transom. Although the flow velocity appears to be relatively constant transversely across the feeder vessel width, it is clearly increasing along the vessels length (lowest at the transom). There is little change in these trends as the vessel moves to 84% docked, but there is a small region of disturbed flow on the lower edge of the flow field image. The start of this disturbance closely aligns with both the transverse and longitudinal locations of the (stationary) propulsor that was fitted to the feeder vessel model (refer Section 2). The final image in the series presents the feeder vessel as it approaches its docked position (93% docked) where the outward flow velocity beneath the feeder vessel clearly increases the closer it gets to the well dock entrance. In this image the disturbance attributed to the propulsor is clearly visible for most of the visible feeder vessel length.

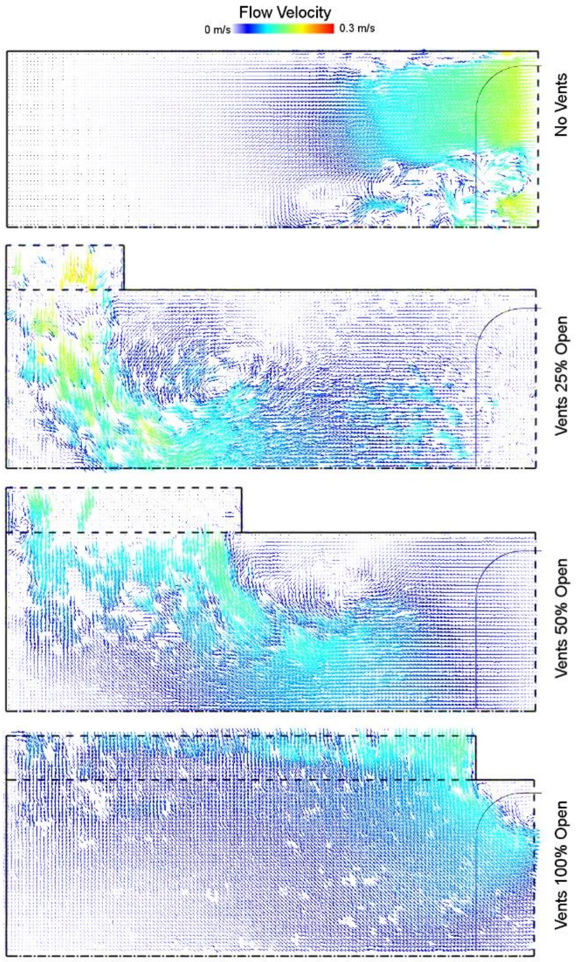

Figure 11: Flow visualisation for the feeder vessel departing across each of the 4 vent configurations for the docking manoeuvre at the steady-state speed of 2.0 knots. The outline of the feeder vessel stern is shown to indicate feeder vessel position.

The flow development during feeder vessel docking at 1.0 knots for the vents 25% open condition is presented in Figure 13. There is no significant variation in the flow field as the docking manoeuvre progresses, however the region of near zero flow remains beneath the stern of the feeder vessel throughout the manoeuvre. Comparing these results to those presented in Figure 12 confirms a dramatic effect on the flow behaviour due to the inclusion of (25% open) vents to permit water to flow out of the well dock as the feeder vessel docks. Importantly, there is a notable reduction in flow velocity around the stern of the feeder vessel for the vents 25% open case, which is expected to improve the effectiveness of the propulsors, hence also controllability of the feeder vessel.

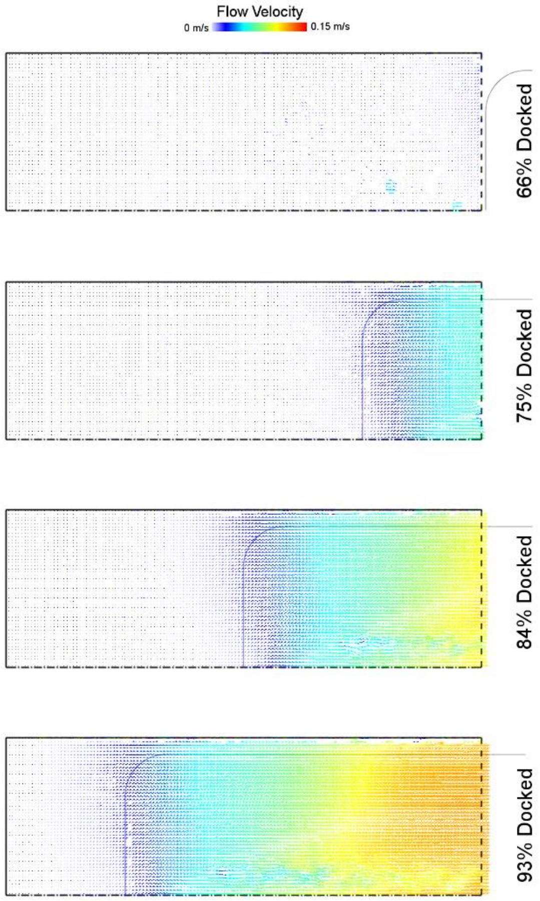

Figure 12: Flow development during the docking manoeuvre at 1.0 knots with no vents for feeder vessel positions of 66% docked, 75% docked, 84% docked and 93% docked.

The same comparison was performed for the feeder vessel departure manoeuvre, as presented in Figure 14 and Figure 15 for the no vents and vents 25% open cases respectively. When there are no vents and the feeder vessel has just begun to depart (93% docked), an even inward flow quickly develops across the width of the well dock beneath the feeder vessel, increasing in velocity along its length, and there is negligible flow aft of the feeder vessel. As the feeder vessel progresses to 84% docked, most of the water in the region aft of the feeder vessel remains quite stationary with a small region of outward flow close behind the feeder vessel. Underneath the feeder vessel experiences very high inward flows due to the quantity of water that is rapidly entering the well dock to fill the void created as the feeder vessel departs. The maximum flow velocity recorded in this region was more than 2.5 times the steady-state departure speed of the vessel. When the feeder vessel has reached the 75% docked position, there is a flow disturbance that originates from the propeller guard of the outboard propulsors (the propeller guards are modelled even though the outboard propellers are not). This region of mixed flow increases in size as the feeder vessel reaches the 66% docked position and the only region of consistent flow is aft of the feeder vessel on the outboard edge of the well dock and flowing towards the centre of the well dock. The region of negligible flow remained quite consistent in size and position from the 84% docked position through until the feeder vessel leaves the frame.

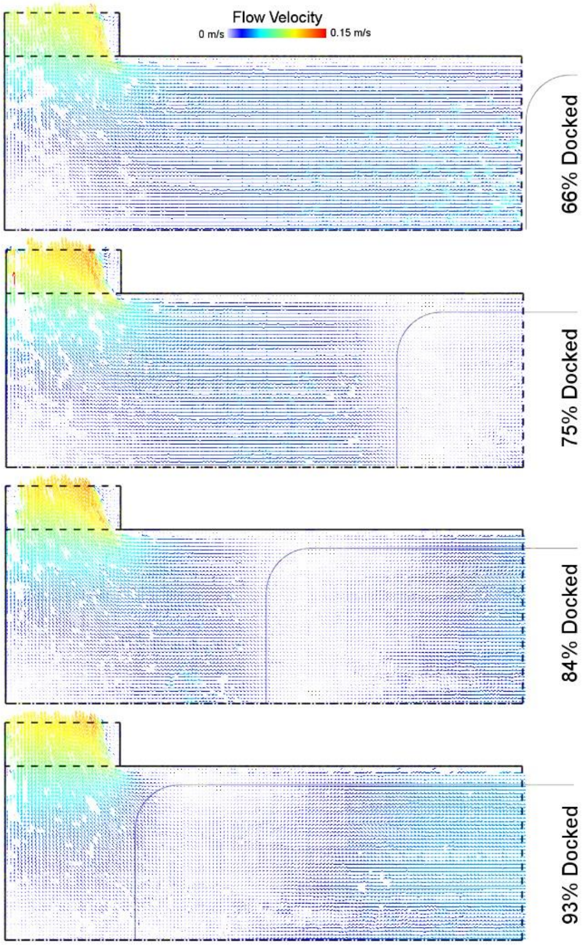

Figure 13: Flow development during the docking manoeuvre at 1.0 knots with the vents 25% open for feeder vessel positions of 66% docked, 75% docked, 84% docked and 93% docked.

The introduction of vents to the well dock again completely alters the flow characteristics for the departure case at 1.0 knots (Figure 15). When the vents are 25% open the flow field is seen to again develop quickly for the departure manoeuvre with a strong inflow through the vent observed when the feeder vessel reaches the 93% docked position. This inflow dissipates upon entry to the well dock and loses most of its velocity within a quarter of a feeder vessel beam from the vent. When the feeder vessel reaches the 84% docked position, the vortex observed during the 1.0 knots departure with 25% and 50% open vents (Figure 9) starts to form slightly aft of the feeder vessel transom. The region underneath the feeder vessel has a small flow velocity throughout the time that the feeder vessel is in the capture frame. When the feeder vessel is 75% docked, the flow field further develops to include a region of steady outbound flow along the centreline of the well dock aft of the feeder vessel. The vortex also begins to move slightly towards the centreline. At the next feeder vessel position (66% docked), the vortex has expanded and reduced intensity and the steady region of outbound flow along the centreline begins to dominate.

Comparison of the flow development between the no vents and the vents 25% open configurations shows that the introduction of the vents reduces the effect from the well dock being enclosed at one end. During docking, the feeder vessel with 25% open vents indicates that there is still some confined water effects under these conditions. These generalised outcomes suggest that the vents 25% open option is close to reaching a balance between mitigating the effects of a closed well dock and the potential increase in relative motions when in a seaway, as considered in the related seakeeping study.

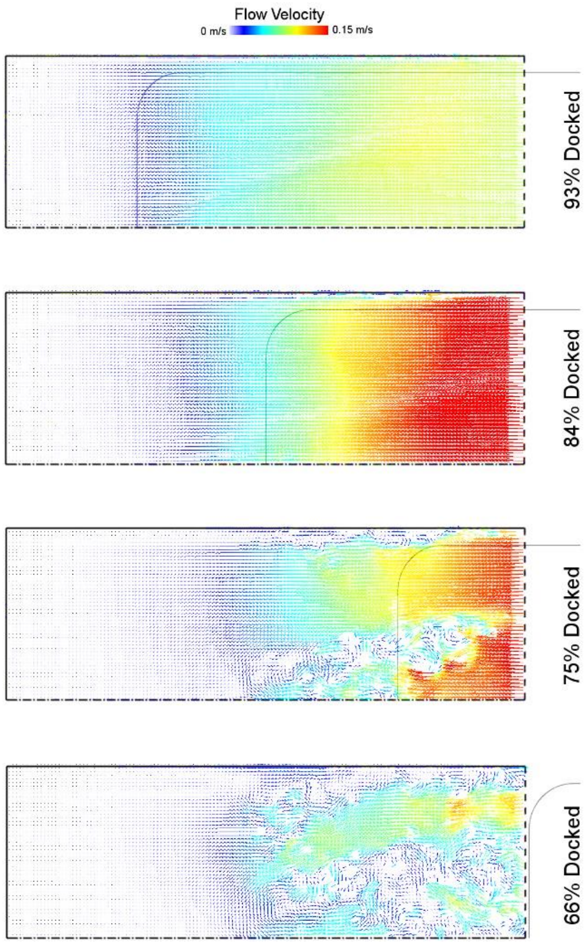

Figure 14: Flow development during the departure manoeuvre at 1.0 knots with no vents for feeder vessel positions of 66% docked, 75% docked, 84% docked and 93% docked.

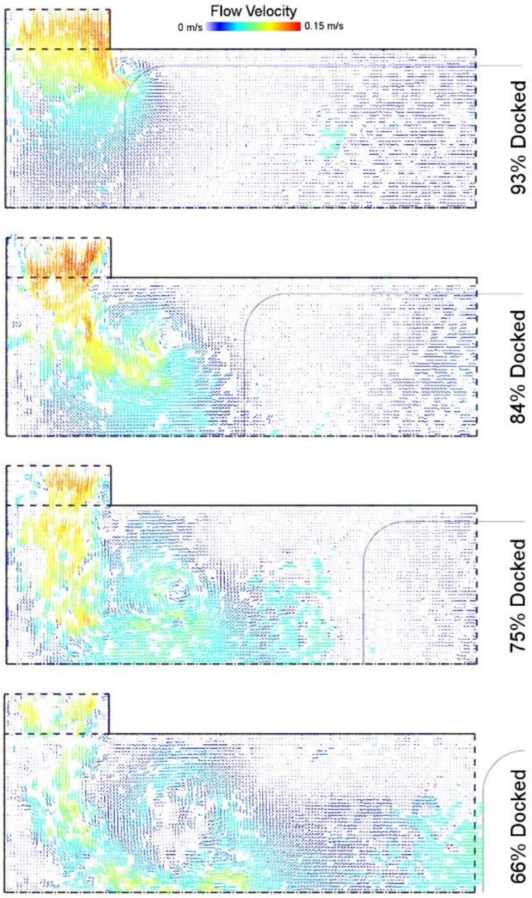

Figure 15: Flow development during the departure manoeuvre at 1.0 knots with the vents 25% open for feeder vessel positions of 66% docked, 75% docked, 84% docked and 93% docked.

4. IMPLICATIONS ON OPERATIONS

Feeder vessel manoeuvring will be safest and most effective when the propulsors are working most efficiently and the feeder vessel is subjected to minimum external disturbing forces. Some of the possible disturbing forces to be minimised are those generated when operating in confined water – with or without a seaway. When in a seaway, the impact of incident waves and swell is reduced due to the sheltering effect provided by the mothership, with the greatest benefit observed when the vent size is reduced (or there are no vents), based on the findings of the wider body of research. Other external disturbing forces could be due to variable or unequal flow around the feeder vessel and its propulsors. The most variable flow around the propulsors in terms of controllability was observed during the docking manoeuvre when there were no vents. Operational conditions significantly improved when vents were introduced indicating that vents are beneficial to feeder vessel operations. The propulsors will perform best when subjected to consistent flow opposite to the motion of the vessel. There were no instances observed where the flow over the propulsors was significant and in the direction of travel of the vessel. In more open vent configurations where there was negligible flow under the aft section of the feeder vessel, the propulsors are expected to behave similar to operations in open water. When no vents were present, very high flow velocities in the opposite direction to feeder vessel motion were observed, causing increased thrust requirements and decreased propulsor effectiveness – ultimately leading to more uncertainty in feeder vessel behaviour. These findings support the inclusion of the vents in the well dock.

It was noted that the inclusion of the vents caused a jet like flow to exit the vents during feeder vessel docking (particularly at higher feeder vessel speeds and smaller vent openings). This flow through the side of the mothership could potentially interact with an ocean going vessel if one were moored alongside. While this is outside the scope of this preliminary investigation, it is expected that this will have no significant influence based on the proposed hull form of the mothership (refer Figure 2).

The docking and departure of the feeder vessel may be influenced by an incident seaway under real world conditions. Now that a good understanding of a baseline case in calm water has been obtained, it is feasible to expand the investigation into docking and departure in a sea state. This may re-introduce the possibility of impact between the vessels during docking and departure and add another dimension to the vent sizing considerations.

5. CONCLUSIONS

An experimental campaign has been undertaken to investigate a feeder vessel entering/departing a well dock whose cross section is only slightly larger than the feeder vessel. The focus of this investigation was on the collection and analysis of flow field data within the well dock of the mothership using 2-dimensional PIV. The docking (feeder vessel moving astern into the well dock) and departing (feeder vessel moving ahead as it exits the well dock) manoeuvres were investigated at speeds of 1.0, 1.5 and 2.0 knots full scale. The effectiveness of well dock vents for mitigating the effects of the confined well dock was determined by comparing three different vent configurations and the base case with no vents.

During the docking manoeuvres a large region of zero (or very low) flow velocity was observed at the enclosed end of the (unvented) well dock. When vents were introduced there was an obvious and generally consistent flow throughout the well dock. During departure the same trend was apparent whereby the no vents configuration caused a region of zero (or low) flow velocity at the end of the well dock and the inclusion of vents led to flow throughout the well dock. The flow became less disturbed as the vent opening was increased. These observations confirmed that the inclusion of well dock vents is very beneficial for the flow within the well dock, potentially leading to a more uniform flow field within the well dock.

There was a stark difference between the no vents and the smallest vent size investigated (25% open) indicating that while the inclusion of vents was most certainly favourable, they did not need to be excessively large to mitigate most effects of the enclosed well dock. A comparison of the flow development between no vents and 25% open vents showed that this minimal vent configuration was sufficient to mitigate the effects of the single ended well dock when the feeder vessel was departing. There was still seen to be significant flow velocity underneath the mid body of the feeder vessel during the docking manoeuvre.

This flow field investigation leads to the conclusion that it is possible to reach a compromise between the docked seakeeping and the docking/departure performance of the feeder vessel. This compromise requires a vent be included to mitigate the effects of the well dock, but a relatively small vent is sufficient to provide a notable reduction of these effects.

6. ACKNOWLEDGMENTS

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