IMPROVEMENT OF ENERGY EFFICIENCY WITH 'INCLINED KEEL' HULL CONCEPT

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ABSTRACT
The EU aims to reduce CO2 emission 20% by 2020 and 80% by 2050, and the marine industries are forced to do their fair share to help the EU to achieve the target. It is important as it is predicted that approximately 50% of European's air pollution will come from shipping by 2020 if no action taken. The most direct way of minimizing the Green House Gas (GHG) emissions is to improve the propulsive efficiency provided by an efficient propulsion system. Among the items of propulsion system, the diameter of propeller should be chosen as large as the hull can accommodate to achieve the highest level of propeller efficiency. Within the framework of large diameter propeller application, the 'Inclined Keel' concept has been around for many years to improve the pulling power of fishing vessels and tug boats. This concept involves the introduction of a small angle of inclination to the keel of a vessel resulting in a smaller draught at the bow and a deeper draught at the aft for the purpose of installing a larger propeller. This paper presents the practical application of inclined keel configuration on a large and competitive container vessel. Application of this concept increased the propeller diameter from 7.9 m to 8.95m while maintaining the vessel's loading capacity. The paper also includes the development of the Inclined Keel hull configuration to prove the worthiness of the proposed design concept with support of numerical design tools and model tests.
Keywords: Inclined Keel, A large propeller Diameter, Energy Saving

NOMENCLATURE

BH	Basis Hull
C_F	Coefficient of Frictional Resistance
C_R	Coefficient of Residual Resistance
C_W	Coefficient of Wave-making Resistance
C_{WA}	Coefficient of Waterplane Area
IKH	Inclined Keel Hull
T_A	Aft Draught
T_F	Forward Draught
WSA	Wetted Surface Area
λ	Scale Ratio

1. INTRODUCTION

In today's world, environmental and economic objectives in the maritime industry go hand-in-hand. It is a well-known fact that more than 90% of the world's goods are carried across the oceans by the shipping sectors and in a generally cost and energy efficient way. This is partly due to its high energy efficiency and relatively low Green House Gas (GHG) emissions. However, one of the most significant current issues in the shipping sector has become to respond to the challenge of ever increasing global pressure over environmental impact issues. Since ocean shipping transportation covers the entire world, the Kyoto Protocol has given the International Maritime Organisation (IMO) Authority to limit and reduce GHG emissions from shipping sector. This resulted in the introduction of an Energy Efficiency Design Index (EEDI), Energy Efficiency Operational Index (EEOI) and ship emissions management plan (MEPC 59, 2009). The environmental performance, therefore, will be part of the competitiveness in new ship-building projects.

On the other hand, shipping companies have had their operating costs hit by ever rising oil prices. Bunker fuel costs have rocketed in recent years due to the demand from the booming economies in Asia and geopolitical stability. Fuel costs already amount to more than half of the operating cost of their fleets due to the high fuel costs, thus ship owners are keen to focus on optimum performance of their vessels in order to save operating cost.

Within the above framework the most direct way of minimising the carbon emission level of a ship is to minimise its fuel consumption. This in turn can be achieved by maximising the propulsive efficiency, provided by an efficient propulsion system and minimising the hull resistance which can be achieved by effective hull form optimization techniques combined with advanced hull drag reduction techniques. One of the ongoing activities of the efficient maritime transportation for the future is the European Commission (FP7) project, STREAMLINE which started in March 2010. The main impact of this project is expected to substantially reduce fuel consumption and emissions by a variety of marine propulsion system, ensuring that waterborne transport is a cost effective, attractive and alternatively to road and air transport. Newcastle University has made an important contribution in securing the funding approval of STREAMLINE project and given the opportunity to thoroughly exploit the application of the large diameter propeller with 'Inclined Keel' concept with a view to improving the propulsive efficiency.

The 'Inclined Keel' concept has been around for many years and is commonly applied to improve the pulling power of fishing vessels and tug boats. This concept involves the introduction of a small angle of inclination to the keel of a vessel resulting in a smaller draught at the bow and a deeper draught at the stern to achieve sufficient immersion of a large diameter propeller. Newcastle University (Seo et al, 2006; Seo et al, 2009a; Seo et al, 2009b) have explored the design and operational benefits of the inclined keel concept using a well-designed 3600TEU container vessel as the 'Basis Hull', whose propeller size has increased from 7.95m to 8.95m. However, increase of total propulsive efficiency is not a simple issue because it is the product of the hull, propeller and relative rotative efficiencies. These investigations also have indicated that, amongst many other hydrodynamic requirements, one of the key requirements for an efficient Inclined Keel Hull is to minimize the bare-hull resistance to fully capitalise the expected increase in the propeller efficiency by adapting larger diameter propeller.

This paper, therefore, focuses on the hydrodynamic development of the IKH, and series of large scale physical model tests conducted at the facility of Pusan National University for the effective design of a large commercial vessel with inclined keel.

2. DESIGN OF INCLINED KEEL HULL

For the same vessel a further increase of propeller diameter would require the development of the new propeller aperture. In order to secure a deeper aft draught for a large diameter propeller a ship could have the 'Inclined Keel' configuration as shown in Figure 1.

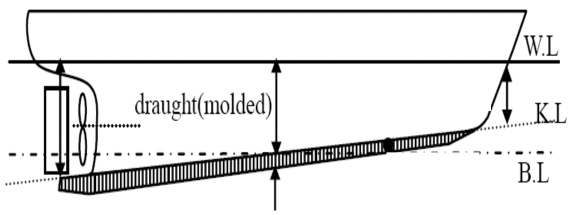

Figure 1: Configuration of the Inclined Keel Hull

A 3600TEU container ship is selected as 'Basis Hull' due to its flexibility of trim control and her propeller diameter is 7.9m. The propeller diameter of the inclined keel hull is increased from 7.9m to 8.95m to take the advantage of improved propeller efficiency, approximately 13% larger than that of the basis hull. Within this context, Takahashi et al. (1984) and Yamano and Iwasaki (1994) reported that 4-6% increase of the propulsive efficiency can be achieved by 12% increase in propeller diameter. To fit an 8.95m propeller diameter in the propeller aperture of BH, the stern profile had to be developed to provide sufficient propeller tip clearances and to attain the required static stability as shown in Figure 2. Hull form development of the inclined keel hull has therefore been carried out with consideration of the enlarged propeller dimension and operating conditions as summarised in Table 1 and Table 2.

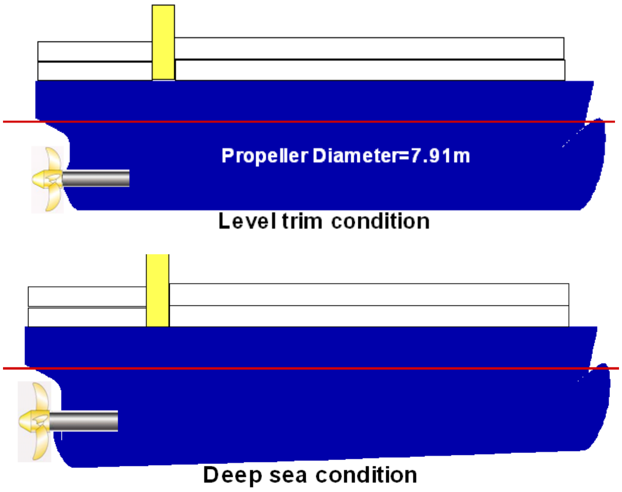

Figure 2: Definition of the Inclined Keel Hull (Upper figure represents the BH and Lower figure represents the IKH)

Table 1: Relative particulars of propeller and aftend

Hull Type	BH	IKH
Distance from baseline to propeller lower tip (m)	0.075	0.15
Propeller Diameter (m)	7.91	8.95m
Distance from propeller upper tip to hull (m)	2.22 (28%D)	2.41 (27%D)
Distance from baseline to hull at propeller plane (m)	10.20	11.41

Table 2: Draughts at different operational conditions

Hull Type	BH	IKH	
Operating Condition	Normal	Harbour	Deep Sea
T_F (m)	11.3	11.3	10.5
T_A (m)	11.3	11.3	12.1

3. HYDRODYNAMIC DEVELOPMENT OF INCLINED KEEL HULL - RESISTANCE

In order to improve the wave-making resistance components generated by the fore body of IKH, the result of resistance is calculated using SHIPFLOW. In order to understand the complex flow in the after body the analysis is conducted using FLUENT 6.3. For this study a three-dimensional, Volume of Fluid (VOF) model to capture the free surface between air and water is employed. The realisable k-e turbulence model, with near-wall function to describe the velocity profile near the wall, is used for turbulent flow. As illustrated in Figure 3, two stage of the IKH development evaluated by resistance and hydrosatic performances is carried out in order to find a final IKH. A design of the IKH is also conducted with the aim of retaining a similar volume and waterplane area to those of BH. A more detailed IKH development is given in the following sections.

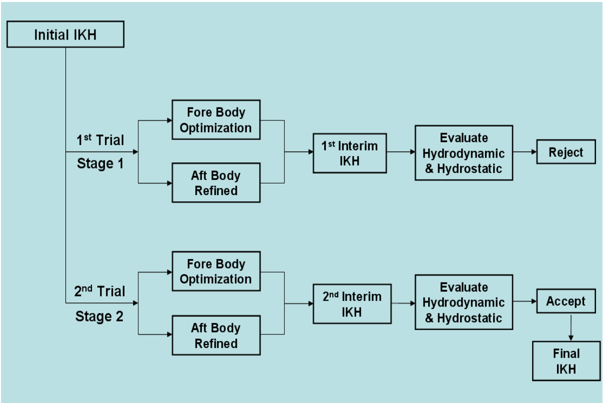

Figure 3: Design stage of the IKH development

3.1 HULL FORM DEVELOPMENT – STAGE1

3.1 (a) Development of fore body

The target for the IKH's fore body development is to reduce the wave making resistance at a design speed 24 knots, yielding a Froude number of 0.252. Fore body modifications, subjected to the fixed volume, is only done starting from the mid-ship position to the bulb since the viscous effect on the wave-making generated from the fore body is negligible. The comparison of the two fore body sections, i.e. before and after modification, is shown in Figure 4. Following the design process, as shown in Table 3, roughly 3-5% reduction in the wave-making resistance was achieved based on potential flow analysis.

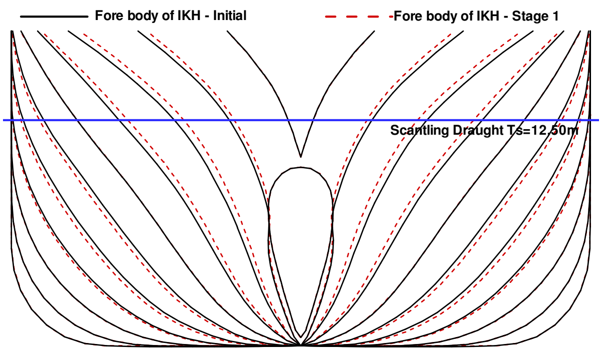

Figure 4: Comparison of fore body plans on level trim condition

Table 3: Improvement of IKH wave-making resistance

		Rw reduction
SHIPFLOW	Pressure integration	3.2%
	Wave cut technique	5.4%

3.1 (b) Development of aft body

For a successful hull form design the development of the fore and the aft body must be conducted with great care due to the complexity of the flow around the body. A design of the aft body of the IKH was conducted with the aim of retaining a similar volume and waterplane area to those of BH. This design approach made the stern bulb of the IKH slightly fatter than that of BH and the aft body sections was designed to have strong curvatures in order to provide enough waterplane area and displacement as shown in Figure 5. The main hydrostatic particulars of both hull forms are also summarised in Table 4.

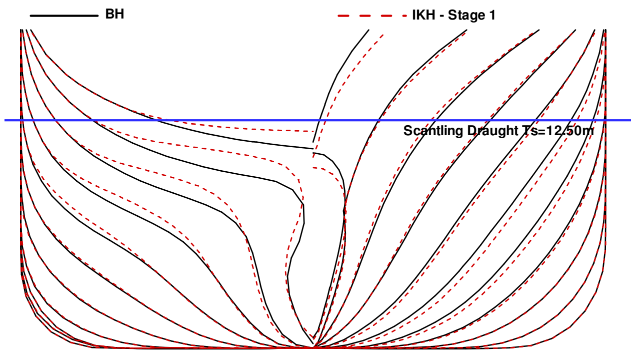

Figure 5: Comparison of body plans on level trim condition

Table 4: Comparison of main hydrostatic particulars of BH and IKH

Main Dimension		Design draught	
		BH	IKH-initial
Lpp (m)		232.8	232.8
Breadth (m)		32.2	32.2
T	T_F (m)	11.3	10.5
	T_A (m)	11.3	12.1
WSA (m^2)		50886	51067
Volume (m^3)		9330	9370
Cwp		0.807	0.807
Propeller (m)		7.91	8.95
Tip clearance		28%D	26%D

FLUENT 6.3 is utilized to evaluate the viscous effect on resistance and wave pattern generated from the IKH. The new IKH shows the increase of the residual resistance coefficient compared to that of BH as shown in Table 5. The wave cut measurement of longitudinal wave profile also carried out at y/Lpp=0.11 for both hulls and are shown in Figure 6. It can be observed that the IKH generated a higher stern wave than the BH

Table 5: Numerical results of residual resistance coefficient from FLUENT

Fn		C_R (×10^3)	Increase
0.252	BH	0.732	5.6%
	IKH	0.773	

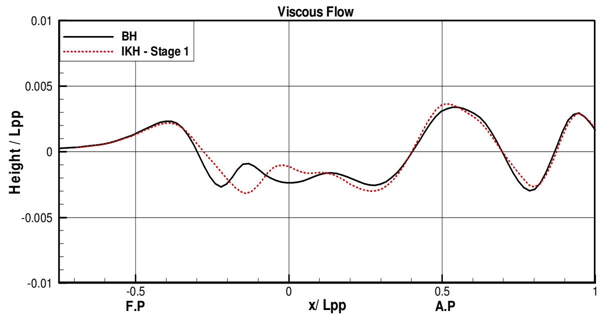

Figure 6: Comparison of wave cuts measured at y/Lpp=0.11

3.1 (c) Model test verification of hull resistance

A physical model test was necessary in order to fully understand the resistance characteristics of the IKH and to further fine-tune its resistance performance. With the courtesy of Pusan National University, physical model tests were conducted in their 100m long towing tank using two models representing the BH and IKH. Table 9 provides the main particulars of the models and of the test conditions for the model experiments.

Table 6: Model dimensions and test conditions

	Full Scale	Model
Scale ratio (λ)	1.0	51.73
Lpp (m)	232.8	4.5
B (m)	32.2	0.622
T (m)	11.3	0.218
Speed (m/s)	12.3467	1.716
Fn	0.252	0.252
Rn	2.53×10^9	7.79×10^7

The measured residual resistance coefficients for the two hulls normalised against the residual resistance coefficient of the BH at the design speed (24 knots) are shown in Figure 7. From this figure it is clear that the residual resistance of the IKH, at around the design speed, was found to be about 7% higher than those of the BH. The increase in the total resistance at full scale was about 3%, as shown in Table 7. The increase of resistance was mainly attributed to the higher residual resistance component and a slightly increased wetted surface area.

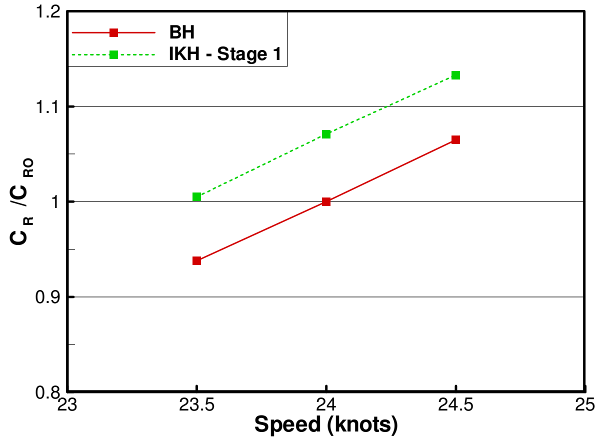

Figure 7: Comparison of residual resistance coefficients (C_{RO} represents the residual resistance of the BH at the design speed)

Table 7: Experimental results from model test

		CF (×10^3)	CR (×10^3)	CT (×10^3)	RT (kN)
Model 1.716 m/s	BH	3.145 (ITTC)	0.8105	3.377	
	IKH –Stage 1		0.8673	3.418	
Full Scale 12.35 m/s	BH	1.367 (ITTC)	0.8105	2.178	1689
	IKH –Stage 1		0.8673	2.234	1740

The viscous solver with free surface improved the accuracy and predicted very close to the experimental. The measurement of longitudinal wave profile also carried out at y/Lpp=0.11 for both hulls and are shown in Figure 8. In the experiment, it is observed that the IKH generated a higher stern wave than the BH as predicted from the viscous solver. In order to make 'Inclined Keel' concept more competitive, there is a need for a more rigorous design approach to minimize the increase of resistance, especially focusing on the modification of the aft body to reduce the stern wave.

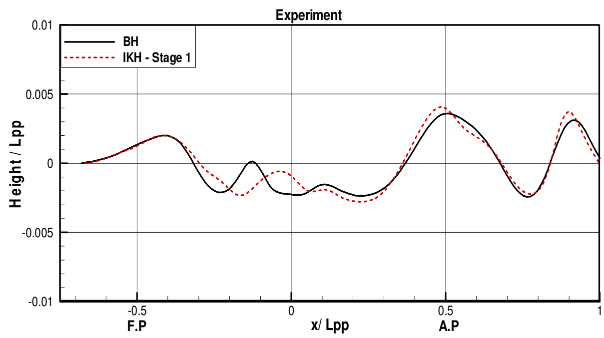

Figure 8: Comparison of wave cuts measured at y/Lpp=0.11

3.2 HULL FORM DEVELOPMENT – STAGE2

3.2 (a) Development of fore body

A second hydrodynamic design stage was performed with the specific aim of adding more volume in the fore body of the IKH. This approach will give more design flexibility with the usable hull volume when developing further the aft body shape. The modification of fore body started from the IKH-stage 1. The comparison of the two fore body sections, i.e. before and after modification, is shown in Figure 9. The reduction of wave-making resistance, computed at Fn=0.252, is summarized in Table 8. Despite the increase of volume, the developed hull form still yields a reduction in the wave-making resistance of 2-3%.

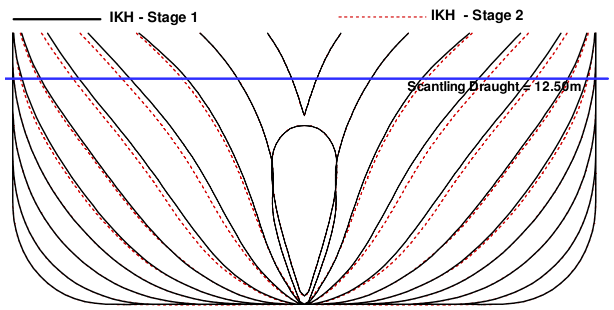

Figure 9: Comparison of fore body plans on level trim condition

Table 8: Improvement of IKH wave-making resistance

		Rw reduction
SHIPFLOW	Pressure integration	2.5%
	Wave cut technique	2.3%

3.2 (b) Development of aft body

Evolving a local form to create a low stern wave within the tight constraints, especially displacement, was the predicament of the IKH development. Within the successful design of the fore body which has a lower wave-making resistance and an added volume, a reasonable compromise for the volume distribution was conducted by moving some volume from the aft body into the fore body while keeping a similar overall level to that of the BH. In order to reduce the immersed wetted surface area near the transom stern and to improve the stern wave, the curvatures of stern sections is better smoothed as shown in Figure 10 and Figure 11 shows the comparison of body plans for the BH and the IKH. As shown in Table 9, the two important hydrostatic particulars, namely volume for payload and waterplane area for stability, is obtained to be close to the BH and the wetted surface area still remained similar to that of the BH.

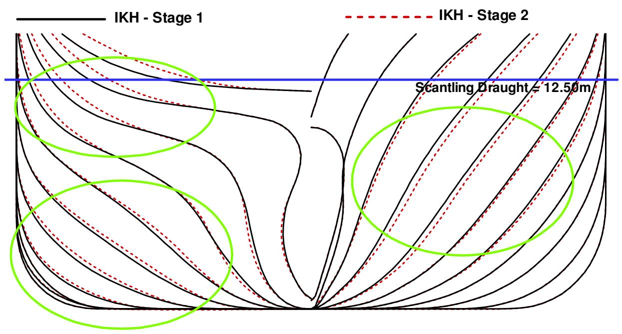

Figure 10: Modification of the IKH

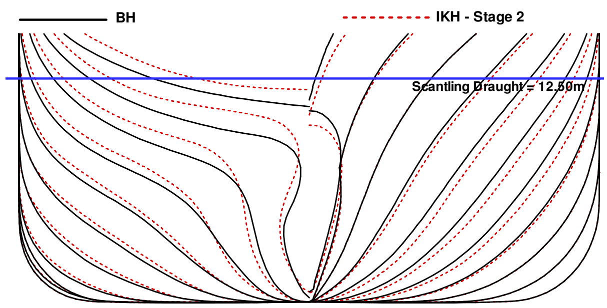

Figure 11: Comparison of body plans

Table 9: Comparison of hydrostatic particulars

Main Dimensions		Design Draught	
		BH	IKH (2)
Lpp (m)		232.8	232.8
Beam (m)		32.2	32.2
Draught	T_F (m)	11.3	10.5
	T_A (m)	11.3	12.1
WSA (m^2)		9330	9330
Volume (m^3)		50886	51177
Cwp		0.807	0.804

FLUENT is again utilized to evaluate the resistance and wave pattern generated from the IKH. The new IKH shows the improvement on the residual resistance coefficient compared to the first IKH and the increase of resistance is only 2.4% compared to that of BH as shown in Table 10. The increase in total resistance therefore remained approximately 1% where the author had targeted the goal in the IKH development. The improvement of the resistance performance is also graphically confirmed by the improved stern wave profiles measured y/Lpp=0.11as shown in Figure 12.

Table 10: Numerical results of residual resistance coefficient from FLUENT

Fn		C_R (×103)	Increase
0.252	BH	0.732	2.4%
	IKH	0.750	

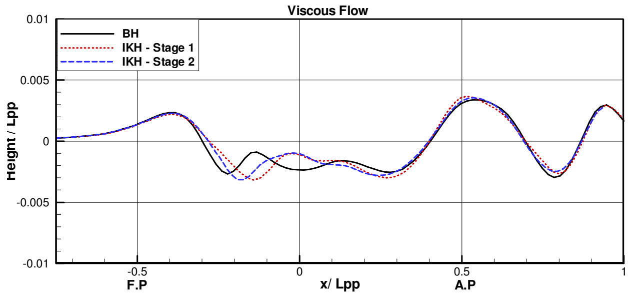

Figure 12: Comparison of wave cuts measured at y/Lpp=0.11

4. HYDRODYNAMIC DEVELOPMENT OF INCLINED KEEL HULL - PROPULSION

In order to demonstrate the effectiveness of the “Inclined Keel” concept, it is prudent to carry out computational evaluation of the hydrodynamic performance of the propeller

4.1 WAKE ANALYSIS

Wake flow analysis is critical from the point of view of the propeller design and performance as well as in assessing any knock-on effect of the wake on the hull resistance. By calculating the viscous flow the 3-D nominal wake distribution of the basis hull as predicted is shown in Fig 12, whilst the wake survey results from the model tests are shown in Fig 13. Despite reasonable agreement between the CFD prediction and the model test results discrepancies still exist between both data sets. In order to improve the accuracy of the wake flow predictions for the IKH, a wake calibration factor, defined as the wake difference between the CFD prediction and model test data, was introduced for more complete wake prediction of the IKH. This wake-calibration factor was applied to the computation results for the IKH wake. The 3D nominal wake distribution for the IKH based on the CFD results with the wake-calibration factor applied is shown in Fig 14 and Fig 15 respectively. The comparison of the circumferential mean wake distribution in the radial direction at the propeller disk was compared for the BH and IKH as shown in Fig 16.

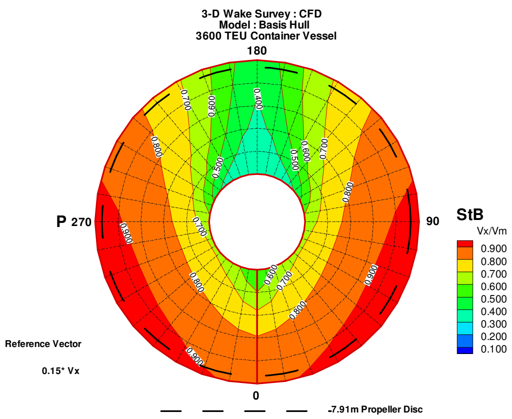

Figure 12: Wake distribution of the BH from CFD

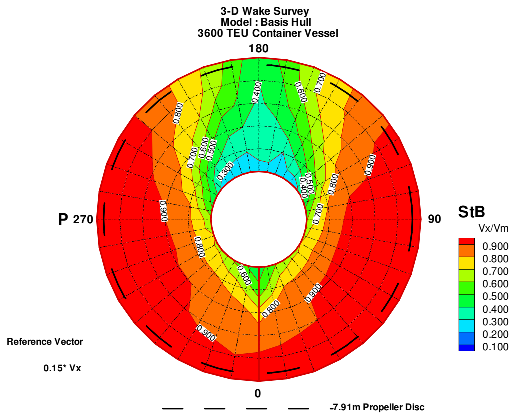

Figure 13: Wake distribution of the BH from experiment

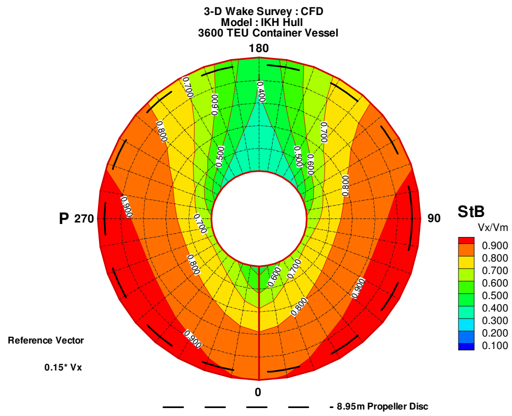

Figure 14: Wake distribution of the IKH from CFD

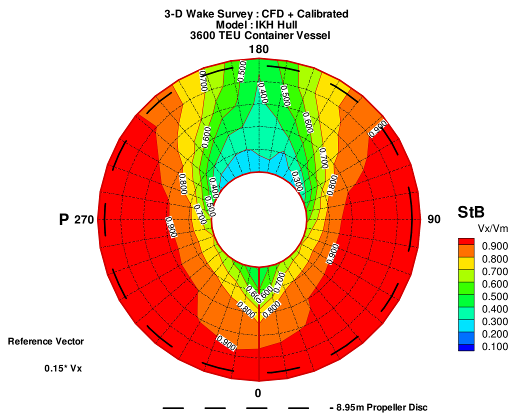

Figure 15: Wake distribution of the IKH from CFD-calibrated

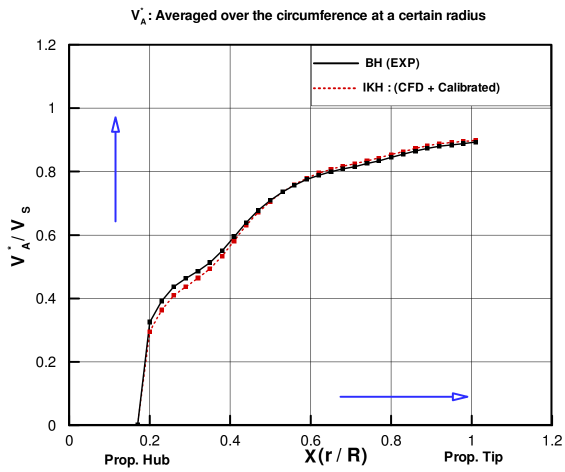

Figure 16: Comparison of the circumferential mean wake distribution

The nominal mean wake, related to the hull efficiency, was 0.235 for the BH and 0.236 for the IKH. Therefore the IKH has a similar hull efficiency as that of the BH however the IKH will experience 1% more resistance when compared to the BH.

4.2 PROPULSIVE PERFORMANCE ANALYSIS

In order to make a fair comparison of the propulsive performance of the two hull forms, the available model propeller test data for the BH was not used. Instead the optimum propellers were designed for the BH and IKH based on the Wageningen B standard series (Lammeren et al, 1969) and Burrill's cavitation criteria for merchant ships. The wake fraction values used are based on the model test data and were calibrated predictions for the BH and IKH, respectively. The thrust deduction factors were assumed the same for both hulls due to the similar resistance and mean wake characteristics; further analysis based on model tests is needed to confirm this assumption.

The open water efficiency for the IKH propeller was 4.1% higher than that of the BH due to the increased propeller diameter and lower propeller shaft rotation. Consequently the IKH was expected to achieve a saving in shaft power of 3.5%, due to the improvement of open water efficiency despite the 1% increase of hull resistance as shown in Table 11.

Table 11: Comparison of basic propulsive performance

	P/D	J	Kt	10Kq	Kt/J2
BH	1.1	0.769	0.209	0.3890	0.354
IKH	1.2	0.876	0.210	0.4273	0.275
	ηo	n (rpm)	Q (KN-m)	PD (kW)	B.A.R
BH	0.66	92.4	2927	28314	0.72
IKH	0.685	72.0	3621	27311	0.64

The cavitation performances of the key blade of the both hull propellers were calculated for every 10 degree around the propeller disc using in-house software. The notation of +/- degrees is with respect to before/after the top dead centre (TDC) respectively when the blade is rotating in a clockwise direction. The cavity volume on the propeller blade, as illustrated in Figure 17, had slightly increased for the IKH propeller because of its larger expanded bladed area. The IKH propeller, however, presents the better performance in terms of a non-dimensional cavity volume based on the cube of the propeller radius, as shown in Figure 18.

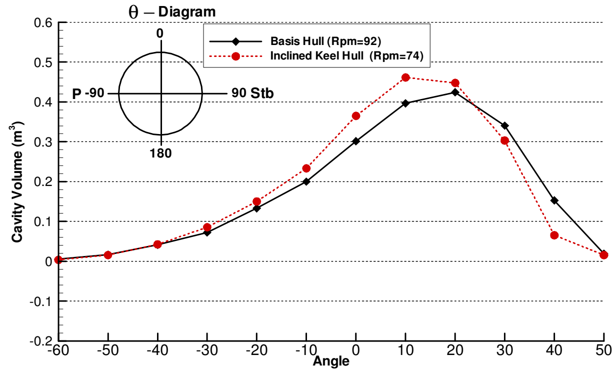

Figure 17: Comparison of cavity volume

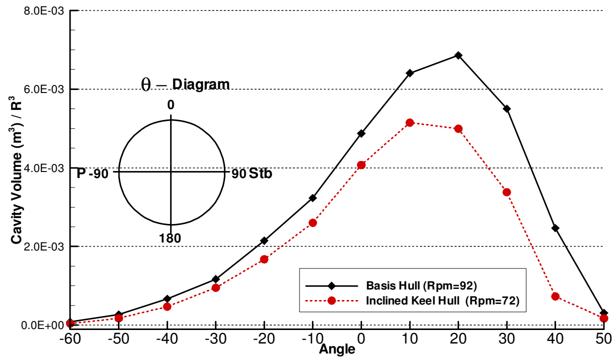

Figure 18: Comparison of non-dimensional cavity volume

5. CONCLUSIONS

This paper presented the progressive development of the IKH in terms of resistance and propulsion performance. The adapted approach is presented along with the selected numerical tools that are required to carry out the CFD analysis for IKH development. Furthermore an assessment of the numerical predictions of bare hull resistance made against model test results is presented. The success of the 'Inclined Keel' application into a large commercial vessel requires a fine balance amongst the minimal or, preferably, no increase in the bare hull resistance, a maximum gain in the propulsive efficiency and satisfaction of other essential naval architectural and operational criteria. From the study of the hull form development, the following conclusions are reached.

1) Full capitalisation of the benefits from 'Inclined Keel' concept requires close attention to the increase in the bare hull resistance due the dramatic modification for the fore and aft body hull and hence requires rigorous hull modifications using sophisticated computational tools and model tests.

2) Remaining of volume and waterplane area at the similar level of those of the BH in the IKH development are essential given vessel's loading capacity. This is successfully conducted with the added volume in the forebody with lower wave-making resistance.

3) Although there is a failure in maintaining the bare hull resistance of the final IKH, 1% increase of total resistance over the BH, this should not significantly negate the expected increase in propeller efficiency by adopting a large diameter of propeller. The preferred final design of the IKH was successful obtained using advanced numerical CFD tools and aided by large scale model testing techniques.

4) The open water efficiency of the IKH propeller improved about 4.1% with the increase of propeller diameter whilst the required power was reduced by 3.5% based on the B-series propeller data. The propeller for IKH also shows the good cavitation performance in the wake shadow region.

The content of this paper is strictly based on the knowledge in the first Author's PhD study. This knowledge currently is being further developed in the FP7 STREAMLINE project through a large scale model test verification programme.

REFERENCES

FLOWTECH, (2011). 'SHIPFLOW User's Manual and Theoretical Manual', FLOWTECH International AB, Gothenburg.

Lammeren, W. P. A. van, Manen, J. D. van, Oosterveld, M. W. C., (1969). 'The Wageningen B-screw series', Transactions SNAME. Vol. 77, pp.115-124.

MEPC, (2009). "MEPC 59th session – report MEPC 59/INF.10", International Maritime Organisation.

Seo, K.C., Atlar, M. & Mesbahi, E., (2006a). 'Efficient propulsion of a container ship using the "Inclined Keel" concept', International Conference on Marine Design and Operation of Container Ships, London, UK.

Seo, K.C., Atlar, Chun, H. H. & Kim., H. J., (2009a). 'Minimization of wave-making resistance for "Inclined Keel" containership', Journal of the Society of Naval Architects of Korea, Vol. 46, No 2, pp. 96-103.

Seo, K.C., Atlar, Chun, H. H. & Kim, H. J., (2009b). 'The inclined keel concept – resistance analysis', International Marine Design Conference, Trondheim, Norway.

Takahashi, M., Umeno, V. & Higasa, N., 'An Analysis on Variation of Propeller Immersion', Journal of Marine Engineering Society, Japan, Vol 12 No 1, 13-20.

Yamano, T., Iwasaki, Y., 'Development of a New Stern Form for Ocean Going Fine Ships', Journal of Kansai Soc. N. A., Japan, No 221, 25-33.