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Effects of cylindrical cruciform patterns on fluid flow and drag as determined by CFD models

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A R T I C L E I N F O

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A B S T R A C T

Fluid flow around and drag of two cylindrical cruciform patterns, conventional (T0) and rotated 45° in its own plane (T45), were numerically investigated by solving three-dimensional Reynolds-averaged Navier-Stokes equations within the subcritical flow regime over angles of attack (AOA) from 90° to 0°. Firstly, the drag for a one-cruciform element was assessed, followed by analysis of a four-cruciform assembly ('square mesh') to take into account the wake effect of tandem elements. For the one-cruciform element, T45 experienced a less prominent streamline separation and consequently lower drag between 90° and 45° AOA, while T0 experienced progressively lower drag below 45° AOA owing to re-establishment of smoother streamlines caused by the gradually reduced circulation momentum from the adjacent vortex that rotates in the off-side direction. For the four-cruciform assemblies, T0 and T45 drag was essentially equal above 45° AOA; while below 45°, T45 had greater drag attributed to more prominent spanwise vortex downstream development. Overall, while the largest relative difference between the two orientations was 26.2% and 33.8% for the one- and four-cruciform configurations respectively at 0° AOA, for 30° and above AOA there were limited drag differences (generally below 10%).

1. Introduction

Global fish production has grown steadily in the last five decades with food fish supply increasing at an average annual rate of 3.2% and more people than ever before relying on fisheries and aquaculture for food and as a source of income (FAO, 2014). Prediction tools for the drag force acting on fishing nets is directly applicable to the work to improve the energy efficiency of trawling and optimise the design of floating fish cages. In the past decade, a large number of researchers have worked on determining the magnitude of forces caused by fluid flow through a netting sheet (Balash et al., 2009; Fredheim, 2005; Lader et al., 2014; Patursson, 2007; Tsukrov et al., 2011; among many others). Some previous studies (e.g., Endresen et al., 2013; Fredheim, 2005) investigated the drag characteristics of net structures for fisheries and aquaculture by considering the cylindrical bar as the basic element. However, simply adding up the forces acting on all the cylinders/twines of a net structure without representing the geometrical feature of intersections/knots in viscous flow provides unreliable predictions of total drag (Fredheim, 2005).

As an alternative approach, a cruciform element, being one intersection of two cylinders each having the length of a mesh bar, can be considered as the basic element of the net structure. The drag force acting on a cruciform and the associated flow field are of great interest over a wide range of practical applications such as heat exchangers, damping screens and various onshore and offshore structures (Osaka et al., 1983a). As reviewed by Klebert et al. (2013), the first investigation of the turbulent wake downstream from a cruciform configuration and the associated drag coefficient (performed by Osaka et al., 1983a, 1983b) noted that the drag coefficient of the cruciform almost coincided with that of the equivalent two-dimensional circular cylinder because the intersecting cylinders are sufficiently long (5-mm diameter and 0.4-m length). Recently, Lader et al. (2014) conducted laboratory experiments on a cruciform structure that was assumed to represent two intersecting twines of the aquatic net. It was found that the cylinders comprising the cruciform without knot/sphere experienced a drag coefficient in a uniform current similar to the established values for an equivalent cylinder.

While, the above studies relate to flow around a cruciform normal to the free stream, there is paucity of research into the variation of drag with respect to cruciform orientation within its own plane and angle of

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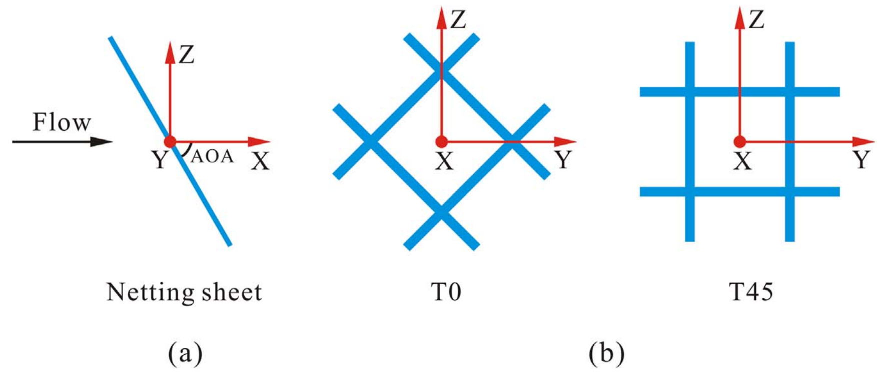

Fig. 1. Definitions of (a) angle of attack (AOA) and (b) T0 and T45 mesh orientation. The mesh-orientation angle is the angle between the mesh axis and the directional cosine of the flow vector on the netting sheet.

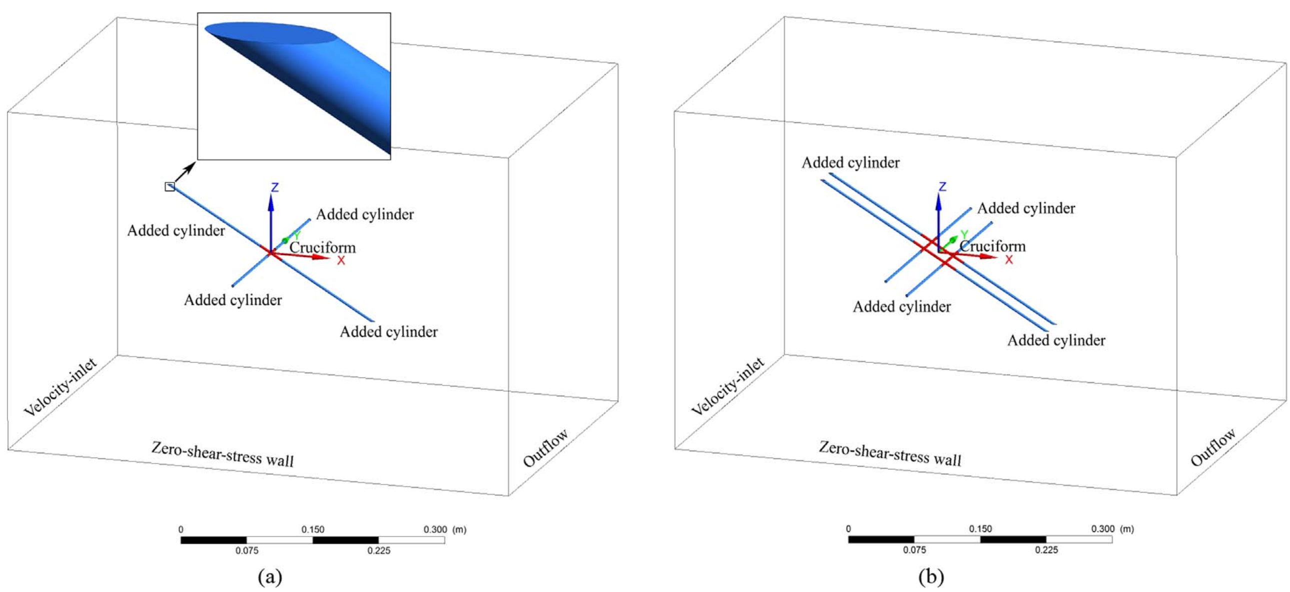

Fig. 2. Schematic view of the numerical model for (a) the one-cruciform element and (b) the four-cruciform assembly (the studied cruciforms in red and added cylinders in blue; For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

attack (AOA) to the free stream. Zhan et al. (2006) derived analytical formulae for the drag force acting on plane nets with T0 and T45 mesh orientation (defined in Fig. 1). The values of parameters within the drag-prediction equations were then established from experimental data for T0 mesh at AOAs from 90° to 30°. Balash et al. (2015) calculated the effect of mesh orientation (T0 vs. T45) on netting drag using the equations developed by Zhan et al. (2006) and compared the result with flume-tank measurements on trawls with alternated T0 and T45 mesh in the side sections and upper/lower panels. Balash et al. (2015) found that the equations of Zhan et al. (2006) indicated that mesh orientation has no effect on drag force when the plane net is normal to the flow (which is intuitive), but when the plane net progressively tilts towards becoming parallel to the flow, the predicted drag for the T0 plane net reduces more rapidly compared to T45. Specifically, the equations suggested a substantial higher drag (by up to ~50%) for T45 nets compared to T0 at 30° AOA. In contrast to this, the measured drag difference for trawls in the flume tank where a large proportion of the netting was alternated between the two mesh orientations was very subtle (~2%). This result occurred for two scenarios: (i) alternation between mesh orientations in the side sections (which are inherently exposed to the flow at ~45° AOA) and (ii) similar alternation in the upper/lower panels (which are near parallel to the flow). While the alternation of T0 and T45 mesh in the principle parts of the prawn trawl showed no practical drag differences, it cannot be conclusively stated that no drag difference exists in other netting configurations. Based on experimental measurements, Stewart and Ferro (1987) estimated that a T45 cod-end experienced approximately three times greater drag than a T0 cod-end. This striking large drag difference was assumed to relate to the surface area difference between T0 and T45 cod-ends, because the T45 cod-end had substantially more open meshes than T0. In this respect, the study did not investigate the difference in drag that might occur between T0 and T45 orientations in a situation where the surface area or mesh opening of the cod-ends was similar (Balash et al., 2015).

Through the review of literature, there is paucity of dedicated and conclusive study on the effect of mesh orientation (T0 vs. T45) on netting drag. Hence, in this study we aimed to examine (using computational fluid dynamics; CFD) the drag effects and flow around meshes of T0 and T45 orientation at AOAs from 90° to 0°. Two models were considered: (i) a one-cruciform element and (ii) a four-cruciform assembly comprising one element subjected to the wake effect from upstream elements.

2. Methods

The one-cruciform element of the studied netting had two 29-mm long intersecting cylinders/twines with a 2.8-mm diameter. The studied free stream velocity was 0.5 m s^{-1}, yielding the subcritical flow regime Reynolds number (*Re*) of 1400. Because an isolated cruciform with free-ends has strong three-dimensional flow characteristics, which