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Flow through nets and trawls of low porosity

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A B S T R A C T

In trawls intended for harvesting marine zooplankton the mesh size and twine thickness may be as small as $O(10^{-4}\,\mathrm{m})$, the porosity less than 0.5 and the appropriate Reynolds number $O(10^0-10^2)$. The flow locally through the meshes varies strongly with the Reynolds number in this range, and the entire flow field, filtered volume and drag of such nets therefore depend strongly on the net parameters and towing velocity.

This paper presents a simplified model for the flow through and forces on inclined permeable screens based on pressure drop considerations. For conical nets the model provides simple expressions for the filtration efficiency and drag as functions of twine diameter, mesh opening, porosity, taper angle and flow (towing) velocity. Comparisons with test tank measurements of typical plankton nets show good agreement.

1. Introduction

Limited commercial fishing for red feed (*Calanus finmarchicus*) is currently being developed in Norway, and in recent years there has been an increase in international fishing for Antarctic krill (*Euphausia superba*) in the Southern Ocean. A *Calanus finmarchicus* individual is typically 0.5 mm thick and 2–3 mm long when it is harvested, while an Antarctic krill is roughly 10 times bigger. Other small zooplankton may also attract commercial interest in the future. The fishing gear used to catch these species is fine-meshed trawls, having low taper angles and large filtering net areas and being towed at low velocities, typically at 0.5 m/s. Except for empirical relations for the filtration performance and clogging rate of small net samplers used in oceanographic research, no satisfactory model for the flow through such nets exists. In future harvesting of zooplankton by means of trawls it will be important to optimize catch and fuel efficiency and catch quality; hence improved hydrodynamic models are needed.

The flow through the main part of traditional fish trawls is usually considered uniform and undisturbed by the trawl. The porosity of such trawls is relatively high, typically $\beta > 0.8$, and the Reynolds number based on twine diameter Re_d is of the order $O(10^3-10^4)$. The drag forces are approximated by summing the drag on the individual twines and knots, using the cross-flow principle for undisturbed flow (towing) velocity and suitable drag coefficients. Several authors indicate that this approach is permissible for $\beta \geq 0.7$, depending also on other net parameters (Hoerner, 1952, 1965; Koritzky, 1974; Paschen and Winkel, 1999; Fredheim, 2005). A model for the flow through trawls of high and intermediate porosities is developed by Fredheim (2005), modelling the twines and knots as line and point sources, respectively, and invoking a velocity defect model for the wakes of the individual twines. Fredheim (2005) states that compared with net panels and net cages, changes in the geometry of a given net cone do not seem to have a large influence on the drag force on the cone, and that the relative pressure variations in front of and inside a trawl are small. The geometry and towing resistance of trawls are often studied in model tests. Different scaling methodologies and empirical corrections exist for the building of the model scale trawl and for the scaling of velocities and forces, but Reynolds scaling is seldom possible and Reynolds number effects are usually neglected (see e.g. Fridman and Carrothers, 1986; Ward and Ferro, 1993; O'Neill, 1993; Ferro et al., 1996; Hu et al., 1999).

In trawls intended for *Calanus finmarchicus* the mesh size and twine thickness will both be of the order $O(10^{-4}\,\mathrm{m})$, the porosity $\beta \approx 0.5$ and $Re_d = O(10^0-10^2)$. The boundary layer outside the twines, i.e. the region of viscous displacement and reduced velocity, generally increases in thickness with decreasing Reynolds number. For high Reynolds number the boundary layer is very thin compared with the twine diameter, while for very low Reynolds numbers the region of viscous displacement may extend several diameters outside the twine. Due to the low taper angle the normal velocity component just in front of the net wall may be very low and combined with the very thin twines in such netting, the resulting Reynolds number Re_d becomes very low. Due to the close spacing between the twines, the entire flow field,

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Symbols

A_0	projected screen area in the direction of U; for a trawl/net cone A_0 equals the mouth area
A_{screen}	total screen (net) area
C_D	overall drag coefficient in the direction of U, normalized by U and A_0
C_L	overall lift coefficient in the direction transverse to U, normalized by U and A_0
C_N	normal force coefficient due to pressure drop K, normalized by U and A_{screen}
d	twine diameter
D	source parameter in Koo and James (1973)
F	filtration efficiency; $F=u_0/U$
F_D	drag force
F_L	lift force
K	pressure drop coefficient
K_0	pressure drop coefficient for $\alpha=90^\circ$
m	mesh bar length
Δp	pressure drop
r	radial coordinate
R	radius of net mouth
R_A	ratio between open-mesh area and mouth area of a net; for a net cone of constant taper ratio and porosity $R_A=\beta A_{screen}/A_0=\beta/\sin\alpha$
Re_d	Reynolds number based on twine diameter
Re_D	Reynolds number based on mouth diameter
T_γ	tangential stress coefficient due to streamline deflection across screen
T_f	tangential stress coefficient due to friction along screen
u_0	the average velocity component in the direction of U of the flow that passes through the screen; for a trawl/net cone u_0 equals the average velocity across the mouth
u_1	normal velocity component just in front of the screen
U	undisturbed flow (towing) velocity some distance upstream of the screen (net)
α	taper angle
β	porosity; for square meshes $\beta=m^2/(d+m)^2$
γ	the angle the flow leaving the screen makes to the normal to the screen
Δ	parameter in Gibbings (1973)
λ	the ratio of the channel height filled by the screen in Koo and James (1973)
υ	kinematic viscosity
ρ	density
τ	tangential stress

filtered volume and drag of such nets therefore depend strongly on the net parameters and towing velocity.

The flow through three-dimensional nets is complex and difficult to model both theoretically and numerically. The purpose of the present work is to provide a simplified parametric model for such flow, so that the effect of varying mesh size, twine thickness, taper angle and other net parameters can be estimated in a relatively simple manner, and to provide a theoretical basis for correct scaling of such nets in model tests. A limited review of the literature on the filtration efficiency of zooplankton net samplers is given, along with a summary of basic results for the pressure drop across permeable screens. The latter are then used to derive a simplified model for the flow through inclined permeable screens. For trawls or net sections of general geometry the resulting equations must be integrated over the net area. For the simple case of a conical net of circular cross-section and constant taper angle and mesh parameters, however, the expressions for the overall filtration efficiency and drag follow directly from those for an inclined screen. Finally, model predictions are compared with measurements for conical nets made out of typical plankton netting.

2. Filtration efficiency of zooplankton net samplers

Zooplankton collecting systems are described in Wiebe and Benfield (2003) and Harris et al. (2000). A much-used design parameter for plankton nets is the “open-mesh-filtering-area to mouth area ratio” R_A. Tranter and Smith (1968) find that the filtration efficiency F increases with R_A for $R_A<3$, while it tends to flatten out for $R_A>3$. Harris et al. (2000) recommend that R_A be at least 6 for horizontally towed nets to have a buffer against clogging of meshes.

Smith et al. (1968) test a series of cylindrical, conical and cylindrical–conical nets (cylindrical forepart, conical aft) in the range $3.2<R_A<6.4$, in addition to one cylindrical net with $R_A=1.6$. The mouth diameter is 1 m and the towing velocity 1.13 m/s for all cases, and F is taken as the ratio between an assumedly representative velocity measured inside the net mouth and one measured outside. The velocity inside the mouth is measured at a distance of $0.7\,R\approx\sqrt{2}/2R$ from the centre of the mouth, i.e. at the radial centre of gravity of the mouth area, cf. Fig. 1. This yields a better estimate of the average velocity across the mouth than the velocity measured at the very centre. Smith et al. (1968) find that the initial filtration efficiency is 85–95% for all but one of the nets, the net with $R_A=1.6$ having an initial filtration efficiency of only 71%. This shows that high initial filtration efficiency can be ensured by proper design, and Smith et al. (1968) and Tranter and Smith (1968) emphasize the sustained (i.e. after clogging occurs) filtration efficiency as the main concern for plankton nets. Smith et al. (1968) present empirical formulas for estimating the minimum R_A necessary for keeping clogging at a satisfactorily low level in waters of different clarity. They find that the cylindrical and cylindrical–conical nets have higher sustained filtration efficiency than the purely conical nets, and attribute this to oscillations in the netting which are more pronounced in the cylindrical sections. They suggest that such oscillation can be promoted by designing the net with a low pressure difference across the net wall (i.e. a low pressure drop), or by reducing the tension in the netting by means of longitudinal support webbing (i.e. causing a slack). They further state that the cylindrical nets were difficult to tow and recover, and therefore generally recommend cylindrical–conical nets.

Tranter and Heron (1967) test net samplers with mouth diameters 0.12–0.57 m, and make measurements and observations

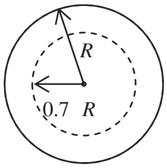

Fig. 1. Circular net mouth with radius R. The area inside the dashed line equals half the mouth area. Smith et al. (1968) measure the assumedly representative mouth velocity at the dotted line ($r=0.7R$) instead of at the mouth center ($r=0$).