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The Interaction of a Lock's Filling Jet and the Ship in the Lock Chamber, Using Scale Model Measurements

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Abstract: *In the design of shipping locks, an accurate prediction of the force on a vessel during levelling is required to ensure a safe but swift operation of the future lock. This force is often predicted by distinguishing several force mechanisms of which the translatory wave, filling jet and density current are generally most important. The present study focusses on the interaction of the filling jet with the ship and aims at understanding how the ship changes the flow pattern and how, consequently, this flow results in a force on the ship. To this end, scale model measurements are performed in a flume with a schematized lock and ship geometry. In addition to measuring the forces on the ship, the flow pattern has been measured using PIV (particle image velocimetry) measurements. The results present a detailed view of the flow pattern in the ship's vicinity. The measured forces are compared to Lockfill and show good agreement despite the simplifications that have been made.*

Keywords: *Shipping lock, filling jet, leveling, force, PIV, Lockfill.*

1. Introduction

The main and obvious purpose of shipping locks is to enable ship passage between two separated water bodies, generally with a water level and/or density difference. In doing this, it is desired to level as quickly as possible and to always guarantee a safe situation. The forces that act on the ship (passed on to the hawsers) are a result of the hydraulic design of the leveling system, the leveling discharge and the position of the ship.

To determine the force on the ship, lock designers can either use a numerical approach or perform measurements in situ or in a scale model. These approaches, however, are often found to be too expensive to execute at the early stages of a project. The leveling process is still difficult and numerically expensive to compute using three-dimensional CFD (computational fluid dynamics), bearing in mind the various hydraulic conditions and ship dimensions to be considered. Therefore, numerical tools exist that can simulate the leveling process quickly (typically in less than a second). Such tools use schematizations of the geometry and of the flow and therefore produce less accurate results, in favor of computational speed. In this way various lock designs and lock operation alternatives can be compared easily.

An example of such a program is Lockfill, developed by Deltares. An extensive description of this program is given in De Loor et al. (2013) and the Lockfill manual. Per July 2015, Lockfill has been made freely available via oss.deltares.nl. Within this study, Lockfill version 5.2 has been used.

Lockfill comprises of several filling systems that work through the lock heads. Examples of such filling systems are openings in the lock gates and short culverts, both used very often in the Netherlands. The computational method distinguishes the following five force origins:

1. The translatory wave in the lock chamber that is generated by a changing discharge in time.
2. The filling jet working directly on the ship's hull.
3. The momentum decrease along the length of the lock which is a result of the discharge and the distribution of the flow velocities, both varying along the lock's length.
4. The friction along the ship's hull and the lock's walls and floor.
5. The density current that occurs in sea locks.

The present study focusses on the effect of the filling jet, which appears in two force components: (1) as a force due to the jet impinging on the ship's hull and (2) affecting the momentum flux in front of the ship as a result of the non-uniform distribution of the flow. This study was initiated in the context of improving the accuracy and applicability of the software Lockfill.

The force due to the filling jet is especially relevant when the discharge into the lock is rather concentrated, and/or the ship is located at only a small distance from the lock's door, where the spreading of the jet is limited. With increasing ship traffic intensity and increasing ship lengths, it is desirable to use existing lock chambers to their fullest capacity. Ships are therefore located closer to the door, possibly in a concentrated jet.

2. Background and Lockfill Schematization

In the mathematical model Lockfill, the lock chamber is schematized as a rectangular container and the ship as a rectangular block. Motion of the ship is not taken into account, apart from the ship moving upward with the mean water level in the lock chamber. The flow rate and water levels are calculated using the conservational laws of mass and energy and the five force components mentioned earlier are computed subsequently.

In this study, the two relevant forces are due to (1) the impinging jet on the ship's hull and (2) the momentum decrease. The force due to the impingement of the jet on the ship's hull inherently takes into account the presence of the ship and, in a schematized way, the shape of the hull. The second force component is a function of the vertical distribution of the jet's flow.

Lockfill assumes uniformity in the width of the lock. Therefore, it considers only spreading vertically and schematizes a spreading according to a jet in a semi-infinite volume of water byusing a geometric description based on Rajaratnam (1976) and derived by Van Kleef (1986). Other formulae describe how the jet entrains water and subsequently returns it, basically describing the recirculation zones the jet induces.

This spreading schematization excludes the Coandă effect, i.e. the tendency of a fluid jet to attach to a surface, being the lock's bottom, one of the walls or the water surface. Furthermore, it excludes the effect of the ship's presence on the flow pattern in the lock.

The spreading of the jet can be adjusted using two input parameters: the orientation of the jet and the spreading angle of the jet. These can be chosen based on the flow pattern found in CFD computations or scale model measurements, or can be used as calibration parameters when forces have been measured in a scale model or in situ.

3. Problem Statement

It is concluded that presently Lockfill assumes that the ship does not influence the jet flow in front of the ship. The research question, therefore, is as follows: to what extent does the presence of a ship in a lock influence the flow pattern in front of the ship and how does this affect the longitudinal force on the ship?

4. Approach

This study comprises of schematized scale model measurements of the fore on a ship due to a filling discharge through a door. The scale model will be discussed in Section 5. A stationary situation will be considered; the discharge and the water level will be constant. The situation can be thought of as one specific instance during the leveling process. The tests will not consider density differences.

As a stationary situation without density differences is considered, the force components due to the translatory wave and due to the density difference will not occur in the tests. The remaining, relevant force components are the following:

- Force resulting from the momentum decrease over the length of the lock.
- The direct force from the filling jet on the bow of the ship.
- The friction between the water flow and the hull, and the wall and chamber floor.

The stationary set-up of the scale model means that the momentum along the lock's length is a result only of the distribution of the flow; the net discharge in these scale model tests is constant along the flume. This differs with reality, where the discharge would decrease to zero along the length of the lock as a result of the leveling process.

The set-up of the tests is based to a large extent on similar scale model measurements which are used to determine the discharge coefficient of a typical lock gate, see Van Velzen & Nogueira (2016) and Van der Ven et al. (2015).

The results of these tests will provide a basis for further validation and/or development of Lockfill and comparable software.

5. Set-Up of Scale Model

The scale model set-up design was two-dimensional, disregarding variations over the width of the lock. Apart from that simplification, common dimensions of locks and inland ships in the Netherlands were used as a basis for its dimensions. The study does not consider a specific lock, rather, it is intended to study the phenomena in a generic sense.

The flume had a total length of 19.2 m. Intakes and outflow of the pumps were located at the ends of the flume. The model gate and vessel were installed in the middle of the flume. Aided by water-dispersing boxes (Jobi boxes), the length of the flume ensured uniform flow towards the model and at a distance downstream of the model. This was confirmed with EMS velocity measurements.

Both the model gate and vessel were made of wood, except for the bow of the vessel. The bow was a Perspex plate, allowing laser lighting in front of the vessel for the purpose of the PIV tests. A small margin on both sides of the vessel was used to prevent any transfer of the force on the vessel towards the flume sides. The set-up is schematized in Figure 1.

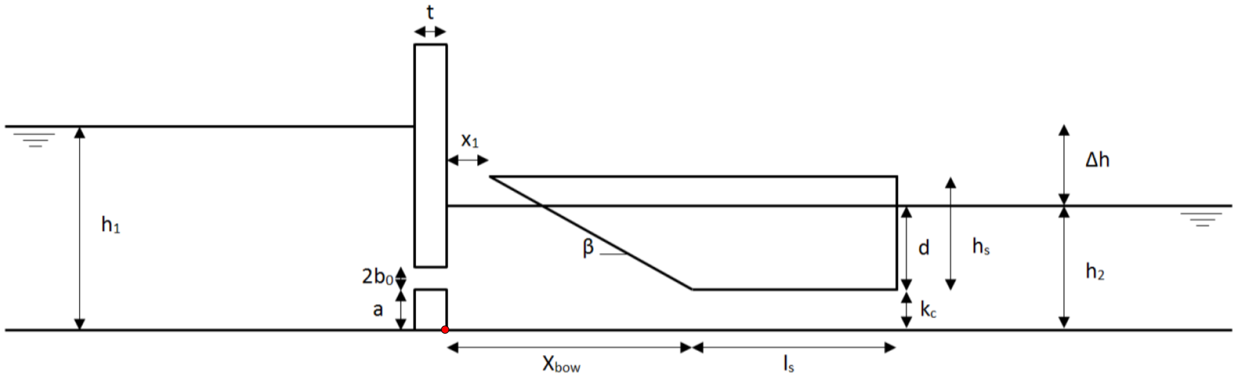

Figure 1. Side-view of the model set-up and geometric parameters used to define the various geometries that were tested. The origin of the coordinate system (x,z = 0,0) is on the flume floor at the downstream side of the gate, denoted by a red dot.

Table 1. Values of the geometric parameters defining the normative situation. Parameter w, marked by an asterisk, denotes the width of the flume (not shown in the figure).

Parameter	Value	Parameter	Value	Parameter	Value
h_1	0.50 m	l_s	0.50 m	$2 \cdot b_0$	0.05 m
h_2	0.30 m	k_c	0.07 m	t	0.08 m
Δh	0.20 m	X_{bow}	0.60 m	β	30°
d	0.23 m	a	0.10 m	w *	0.50 m

The flow measurements consist of multiple EMS (electromagnetic flow velocity) point measurements at various locations and PIV measurements directly downstream of the lock gate. These measurements were conducted as separately, and all of these consider the vessel at the normative position (see Table 1). Additionally, force measurements were performed for various scenarios.

6. Results

6.1. Availability of All Measurement Results

The dataset resulting from this study is shared entirely; those interested can contact Deltares or download the data via the 4TU Research Data repository, data.4tu.nl. (Direct address: https://doi.org/10.4121/uuid:0aff8af7-9baa-40be-8f4f-45bed1b31062).

The results comprise of vertical flow profiles obtained with EMS instruments at various locations, detailed flow measurements with PIV in front of the bow and force measurements of various situations, most importantly varying the position and keel clearance of the ship. Only a selection of these results is included in this paper; for a more complete discussion, the reader is referred to the project's report, Van Loon (2017).

6.2. Detailed Flow in front of the Ship, Measured Using PIV

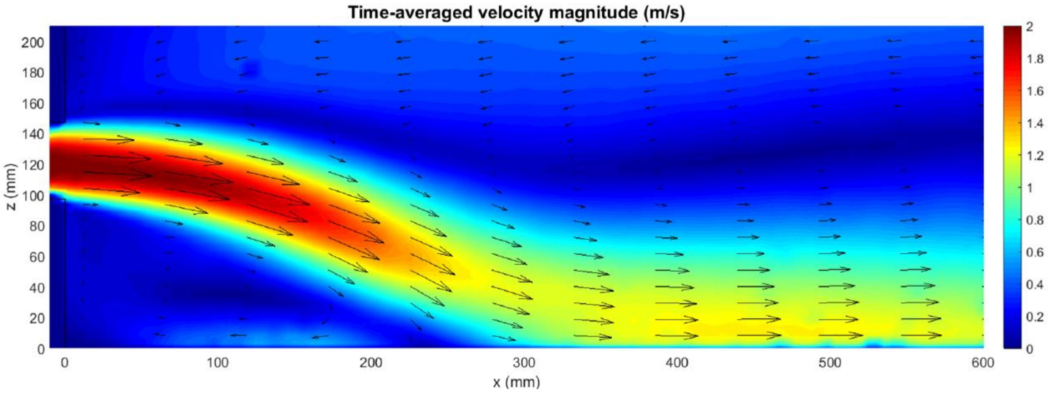

Figure 2. Velocity magnitude found with the PIV measurement without ship.

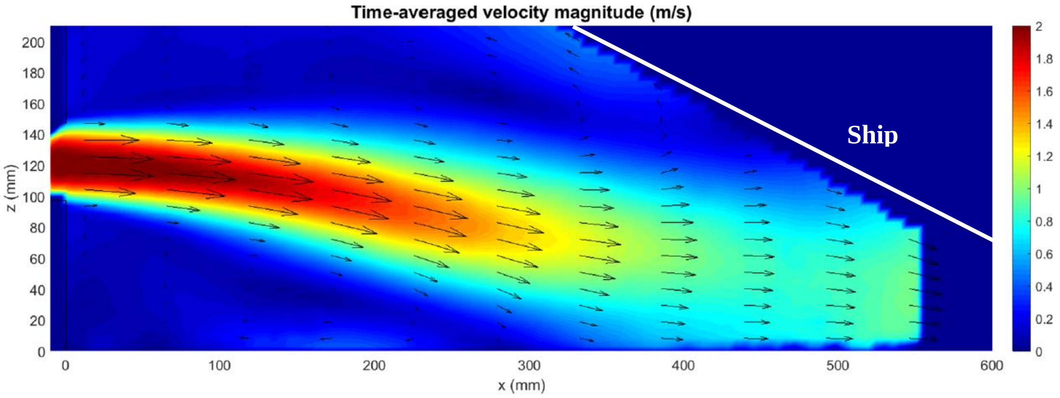

Figure 3. Velocity magnitude found with the PIV measurement with ship.

There are some significant differences between the flow pattern in an empty flume versus the flow pattern when a ship is present. The jet without ship shows to attach more strongly to the bottom, i.e. the point of attachment is closer to the gate. The angle of the jet for the case without ship, Figure 2 is estimated at -13° with respect to the horizontal. In Figure 3, this reduces to approximately -8°. Secondly, the jet spreads over a bigger portion of the water depth when a ship is present. It is shown that the jet without ship does not spread upwards at all before the jet is attached to the bottom. Note the missing areas along the ship's hull that result from processing limitations in the PIV technique. Finally, stronger velocities near the bottom are observed in the jet in the measurement without ship.

7. Discussion

7.1. Analysis of the Momentum Flux of Lockfill and PIV Measurements

7.1.1. Formula to Determine the Momentum Fflux

The influence of the presence of the ship will be analyzed by determining the momentum flux from the velocity profiles in front of the bow, using Eq. (1).

$$S_x = \rho b_l \int_a^b u_x(z)^2 dz \tag{1}$$

With

S_x	The momentum flux in the x-direction [kg·m/s^2]
b_l	The width of the flume [m]
$u_x(z)$	The flow velocity in x-direction, as a function of the vertical coordinate z [m/s]
a,b	The bottom and top of the jet, defined as the coordinates where the velocity equals zero [m]
ρ	Density of the water [kg/m^3]

It is assumed that the velocity profile in the center of the flume is representative for the entire width. In reality, the deviations from the center velocity are indeed found to be sufficiently small. As the interest lies in the momentum flux in the jet, only the positive velocities are considered in the calculation.

7.1.2. Velocity Profiles in Lockfill

Figure 4 shows the velocity profiles as schematized in Lockfill. The upper plot considers a horizontal jet, i.e. an angle of 0°. The lower two plots consider the angles that could be recognized in the PIV results: -8° (middle plot) and -13° (lower plot).

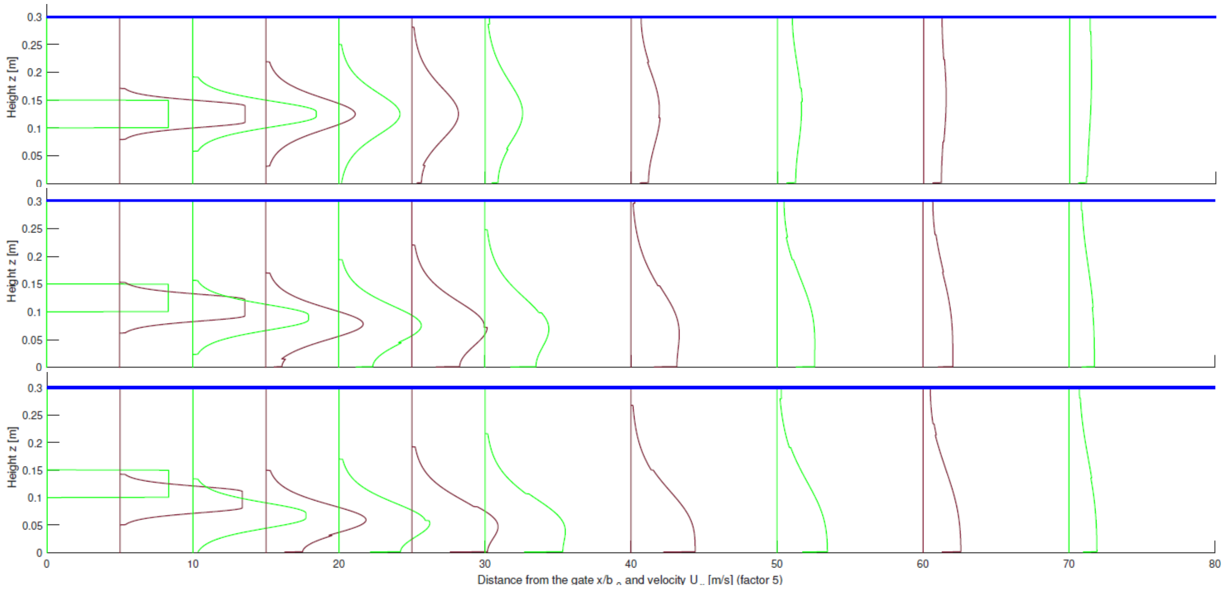

Figure 4. Velocity profiles from Lockfill with jet angles 0°, -8° and -13°. (Velocities scaled with a factor 5).

As described in Section 2, Lockfill assumes a certain spreading of the jet and includes the entrainment of water from the eddies surrounding the jet. The velocities it calculates, however, only show the positive velocities. The zones where velocities are indicated to be zero would not be still water in reality; the return flow of the induced eddies would occur there. Since only the positive velocity of the eddies is part of the jet schematization, the discharge in the jet, Q, is not constant but increases and decreases along the flume length.

7.1.3. Discharge in the Jet, Comparing Lockfill and PIV

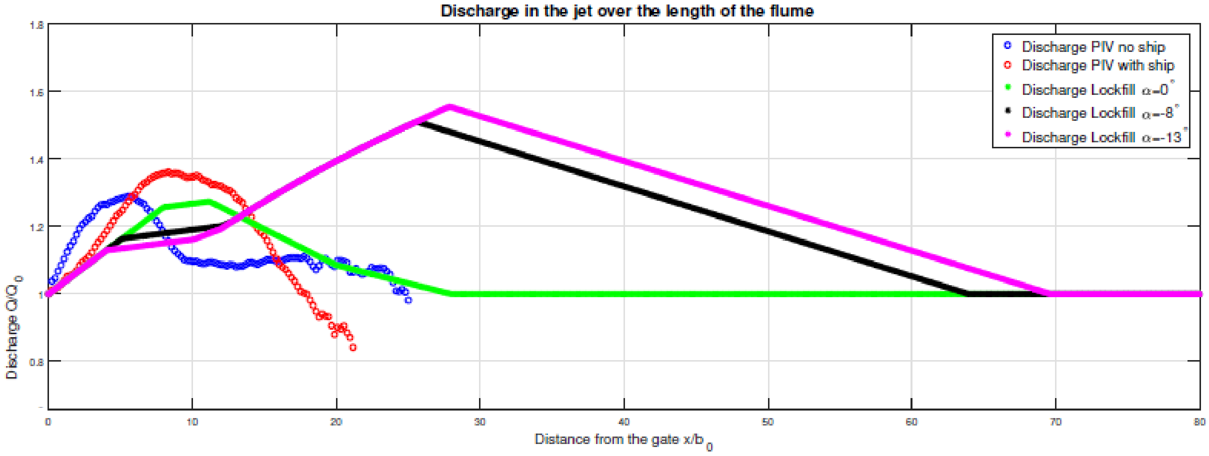

Figure 5. The positive discharge in the jet for the Lockfill schematization and PIV (location of the ship $x/b_0 = 24$).

Figure 5 displays the positive discharge in the jet over the length of the flume. The jet shows to entrain water from the surrounding eddies.

Since the Lockfill schematization does not include the presence of a ship, entrainment can occur in the zone where the ship is located in reality. Downstream of the eddies, the discharge is equal to the incoming discharge Q_0. When the jet angle chosen is increasingly negative, the upper eddy will become larger, increasing the maximum discharge and moving the maximum discharge further from the gate. This can be recognized in Figure 5 when comparing the black and purple lines.

The discharge has also been determined based on the PIV measurements computed from the velocity profiles. Note that the discharge resulting from the measurements with a ship decreases to less than the initial discharge, which is not expected since mass conservation dictates that the discharge at least equals the incoming discharge Q_0. The difference is likely explained by the missing area in the PIV section, see Figure 3.

The shape of the discharge curves shows similarities. However, the measurements indicate that the increase and decrease occurs quicker than Lockfill predicts. This has to do with the presence of the ship and the (permitted) size of the eddies.

7.1.4. Momentum Flux in the Jet, Comparing Lockfill and PIV

The momentum flux in the jet is both dependent on the discharge in the jet and the velocity of the jet. The direction of the jet is also of interest since the momentum flux is considered in the x-direction specifically. Four different processes need to be taken into account when studying the results displayed in Figure 6 below.

1. The increase of total discharge in the jet due to the entrainment of water from the surrounding eddies.
2. The decrease of total discharge in the jet as a result of the jet losing water to the eddies.
3. The spreading of the velocity over the height of the flume; lower velocities yield a lower momentum flux.
4. The direction of the jet with respect to the horizontal; the momentum in the x-direction is being considered, therefore a higher angle will yield a lower momentum flux.

The momentum flux derived from the PIV with and without ship is shown in Figure 6 along with the momentum flux based on the Lockfill schematization.

It can be seen that the line representing the case without ship decreases earlier and faster than the case with ship. This can be explained as a jet that curves towards a boundary (i.e. aligns towards the vertical) loses momentum in the x-direction quickly. In contrast, a jet that remains horizontal only has momentum in the x-direction. The same can be observed in the lines denoting the Lockfill schematization of the jet, based on various jet angles.

Once the entrainment of water from the surrounding eddies stops, the jet will quickly lose momentum. As discussed earlier, the location at which the loss of momentum flux starts depends on the angle of the jet.

There is a big difference between the case with and the case without ship. This leads to the conclusion that the inclusion of the ship in the calculation method has a significant influence on the prediction of the momentum flux in front of the bow. In general, the trends measured with PIV are similar to the trends from the Lockfill schematization; however, the values can deviate significantly.

The momentum flux in the case with ship is most similar to the horizontal jet. The exact cause of this can most likely be explained by the ship blocking the flow, avoiding the occurrence of the larger upper eddy observed in the case without ship. This prevents the jet from attaching to the bottom. Consequently, a schematization with a horizontal jet will provide the most accurate results when calculating the forces on the ship.

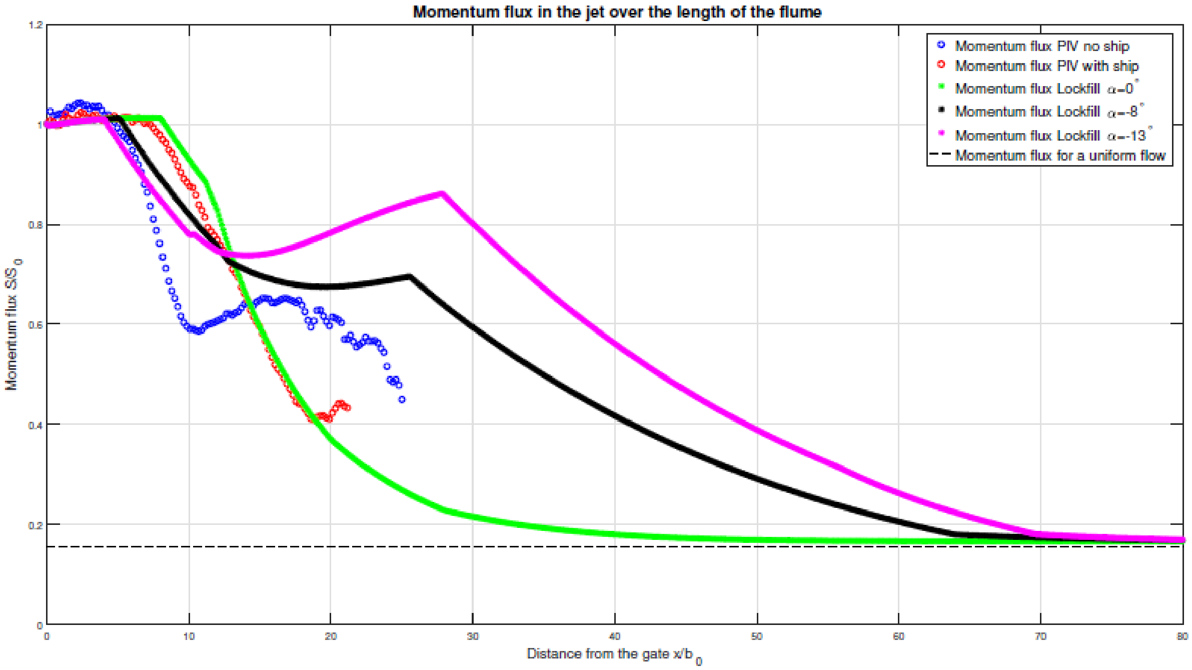

Figure 6. The positive momentum flux in the jet for the Lockfill schematization and PIV measurements.

7.2. Calculating the Force on the Ship Using the Flow Schematization in Lockfill

The momentum flux can be computed from the Lockfill jet schematization; this is done by calculating the momentum flux from the schematized flow distribution. Subsequently, the force on the vessel can be calculated from this momentum flux using Eq. (2).

$$F_{\mathrm{ship}} = S_a + \tfrac{1}{2}\rho g b_l h_a^2 - \rho \frac{Q^2}{A_b} - \tfrac{1}{2}\rho g b_l h_b^2 \qquad (2)$$

With

F_{ship}	The resulting force on the ship [N]
S_a	The momentum flux in the jet, in front of the bow, calculated from PIV, given by Eq. (1) [kg·m/s^2 = N]
ρ	Density of the water (1000) [kg/m^3]
g	Gravitational constant (9.81) [m/s^2]
b_l	Width of the lock [m]
h_a, h_b	The water level at position a, b [m]
Q	The discharge [m^3/s]
A_b	The wet cross-sectional area at location b (width of the flume x water depth)

As stated in Section 4, the force on the vessel also depends on the direct force of the filling jet on the ship's bow as well as the friction force on the water flow. Lockfill takes this into account through the water levels h_a and h_b,. The computation of h_a and h_b is given in detail in the Lockfill manual.

When Lockfill uses a horizontal jet, the formula results in a longitudinal force of 48.8 N. A force of 50.1 N results when assuming a jet angle of -13°. Both agree well with the measured force of 46.2 N.

It can be expected that the schematization of the flow has a big influence on the result of such computation when the ship is placed further downstream of the gate. When the ship is placed close to the door, the travel distance of the jet is simply too short for the jet to spread much or for it to attach to a boundary. The accuracy of the spreading schematization is of lesser importance there—invalid assumptions in this schematization will only affect the resulting flow distribution to a relatively small degree. Further away from the door, however, the distribution of the flow heavily depends on the spreading schematization. Currently, the schematization does not include the attachment of the jet to the bottom. When the jet would be attached to the bottom, the spreading over the height is limited; therefore, the momentum flux in the jet would remain high.

7.3. Calculating the Force on the Ship Using the Measured Flow

The measured force on the ship can be reproduced using the measured flow. To perform this calculation both the velocity profile and water level upstream and downstream of the ship must be known. In front of the ship's bow, 0.10 m downstream of the door, both the average water level and a full velocity profile are measured. At a position downstream of the ship, 5.1 m from the gate, another wave height meter has recorded the water level. It is confirmed by measurements (not shown here) that the velocity there is practically uniform over the depth.

Again, the force on the ship is determined with Eq. (2). The measurement locations at 0.1 and 5.1 m from the gate are taken as locations 'a' and 'b' respectively. Doing so, the direct force of the filling jet and the friction force are taken into account implicitly as they affect these measured water levels. The momentum flux S_a is computed from the flow field resulting from PIV.

This results in a total force F_{ship} of 47.9 N, a slight overestimation of the total measured force in normative position, which is 46.2 N. From this it follows that a prediction of the momentum flux can be used to predict the force on the ship.

7.4. Overview and Comparison of the Various Methods to Obtain the Force on the Ship

The force has been determined using Lockfill computations with varying jet angles, has been derived through the momentum flux based on PIV, and has been measured directly with force transducers on the model ship. Table 2 gives an overview of these results.

Table 2. The momentum flux in front of the bow S and the resulting longitudinal force on the ship F_x for different methods.

Method	Momentum flux at $x = 0.15$ m [kg·m/s^2]	Resulting force [N]	Relative error
Measured with force sensors	n.a.	46.2	0%
Based on PIV, with ship	70.1	47.9	+3.7%
Based on PIV, without ship	63.7	62.3	+35%
Calculated with Lockfill, horizontal jet	69.9	48.4	+4.8%
Calculated with Lockfill, jet with angle $\alpha = -13°$	63.8	50.1	+8.4%

The force is predicted accurately using the momentum flux derived from the PIV measurements of the case with a ship present. The force predicted with the PIV measurements without ship, however, differs significantly from the measurement. This again indicates the effect of the presence of the ship on the flow field and subsequently on the force on the ship.

Lockfill shows good agreement with a minor dependency on the chosen jet angle. Note that this considers the case with the ship close to the door in which case the Lockfill schematization performs well.

8. Conclusions

It was found that the presence of the ship reduces the deflection of the jet towards the bottom. The reason for this is the interference of the ship's bow with the eddy in the upper half of the water depth. The presence of the ship thus has a significant influence on the flow pattern in front of the ship.

In the schematization currently used in the numerical program Lockfill, the eddies in the lock chamber, induced by the filling jet, are not confined by the ship's bow and may comprise part of the volume that is the ship. By overestimating the size of the eddy, the entrained discharge and momentum are overestimated as well, affecting the predicted force. As a result, the best agreement between measured and computed force in the considered case is found when Lockfill assumes a horizontal jet, even though the PIV measurements show the jet to be directed 8° downwards with a vessel present (and 13° downward in an empty flume).

Comparing the PIV measurements to the Lockfill schematization shows that the Lockfill schematization predicts the momentum flux in the jet accurately close to the lock door. However, further away from the gate, the jet angle in the Lockfill schematization can be expected to have a big influence on the momentum flux. This is a result of the Coandă effect not being included in the current Lockfill schematization. The Coandă effect can be approached in Lockfill by direction towards the lock floor or water surface. This will also reduce the spreading of the jet; although overestimation of the spreading will be clear at larger distance from the door.

This study shows that Lockfill predicts the forces on the ship well as long as the momentum flux in front of the bow is calculated accurately. Using the PIV measurements to the Lockfill and the EMS point measurements, a momentum balance could be made over the ship. This momentum balance can predict the force on the ship accurately from which it can be concluded that the force can be predicted using the measured flow.

It is recommended to include various vessel shapes or gate designs in future research. Moreover, getting detailed PIV flow measurements of a further variety of the vessel's position with respect to the gate is beneficial.

9. Acknowledgements

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