# KHIONE

## Validation Manual

Version v8p5
December 1, 2023

# Contents

# 1. Border ice formation

## 1.1 Purpose

This test case demonstrates that KHIONE is capable of modeling border ice formation and its interactions with temperature, frazil and hydrodynamics. A linear thermal budget formulation is used with an air temperature set to $-15°C$. Water is running down a meandering trapezoidal flume.

## 1.2 Description

### 1.2.1 Geometry, mesh and bathymetry

The domain is a sinusoïdal flume with a trapezoidal bottom, boxed within $(x = -60, y = -30)$ and $(x = 320, y = 25)$. The mesh of the domain was created with a uniform density and with 23960 elements and 12600 vertices (cf. figure 10.1).

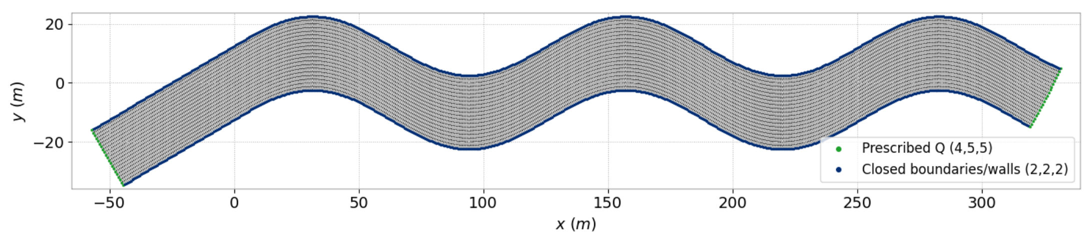



Figure 1.1: Domain mesh

### 1.2.2 Initial conditions

A hydrodynamics steady state condition is established first separately to reach a constant and uniform elevation of $2.5m$ and a constant and uniform discharge of $10m^3/s$. Water temperature is initially set at $0.002°C$ and frazil volume fraction at $10^{-4}$. These values are also used for the upstream boundary condition.

### 1.2.3 Boundary conditions

There are two solid boundaries and 2 open boundaries. The solid boundaries are on either side of the length of the flume, considered as solid walls with perfect slip conditions. A constant discharge of $5.0m^3/s$ is imposed at the upstream and downstream boundaries with a temperature set to $0.002°C$. A first simulation is carried out with for the hydrodynamics only to get to a steady state equilibrium of a constant and uniform elevation of $2.5m$ and a constant and uniform discharge of $5m^3/s$ along the entire length of the flume.

### 1.2.4 Atmospheric drivers

For this test case, linear heat exchanges are used i.e. within the KHIONE steering file:

- ▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*
- ▷ *SOLAR CONSTANT = 0.*
- ▷ *WATER-AIR HEAT EXCHANGE CONSTANT = -50.*
- ▷ *WATER-AIR HEAT EXCHANGE COEFFICIENT = 20.*

Air temperature is set to a constant of $-15°$ during the simulation.

### 1.2.5 Physical parameters

In order to balance the slope and the discharge through the flume, a Manning friction law is used, with a coefficient of 0.025.
To activate the simulation of border ice processes, the following keywords are added to the KHIONE steering file:

- ▷ *BORDER ICE COVER = YES*
- ▷ *ICE COVER IMPACT ON HYDRODYNAMIC = YES*

Border ice formation is triggered by three conditions. Water surface temperature $T_{ws}$ must be inferior to $T_f - T_{cr}$, with $T_f$ the fusion temperature of water and $T_{cr}$ an empirical critical temperature defined by $-1.1°C$ by default. Aditionnally, local depth averaged velocity must be inferior to a critical velocity $U_{cr}$ defined by $0.07m/s$ by default. Finally frazil buoyancy velocity $U_b$ must be superior to the local vertical turbulence velocity $U_z'$. $T_{cr}$ and $U_{cr}$ can be modified in the KHIONE steering file via the following keywords:

- ▷ *CRITICAL VELOCITY FOR STATIC BORDER ICE = 0.07*
- ▷ *CRITICAL WATER TEMPERATURE FOR STATIC BORDER ICE = -1.1*

The variables $U_z'$ and $T_{ws}$ are determined via empirical relations. $T_{ws}$ depends on the channel width (fixed to $15m$ by default) that can be adjusted via the following keyword in the KHIONE steering file:

- ▷ *CHANNEL WIDTH FOR THE COMPUTATION OF SURFACE TEMPERATURE = 25.*

### 1.2.6 Numerical parameters

The time step is set to $1s$ and the number of timestep is set to 1800 which leads to a simulation time of 30 minutes.

## 1.3 Results

On th following figures bathymetry, velocity, temperature, frazil volume fraction, surface ice type and ice cover thickness are plotted respectively. During the simulation, a layer of static ice cover develops on the river banks which have a significant effect on the water temperature as it tends to isulate the river. As a consequence this tends to lower the amount of suspended frasil ice being formed along the river. Note that there is no mass exchange between suspended frazil ice and ice cover in this simulation.

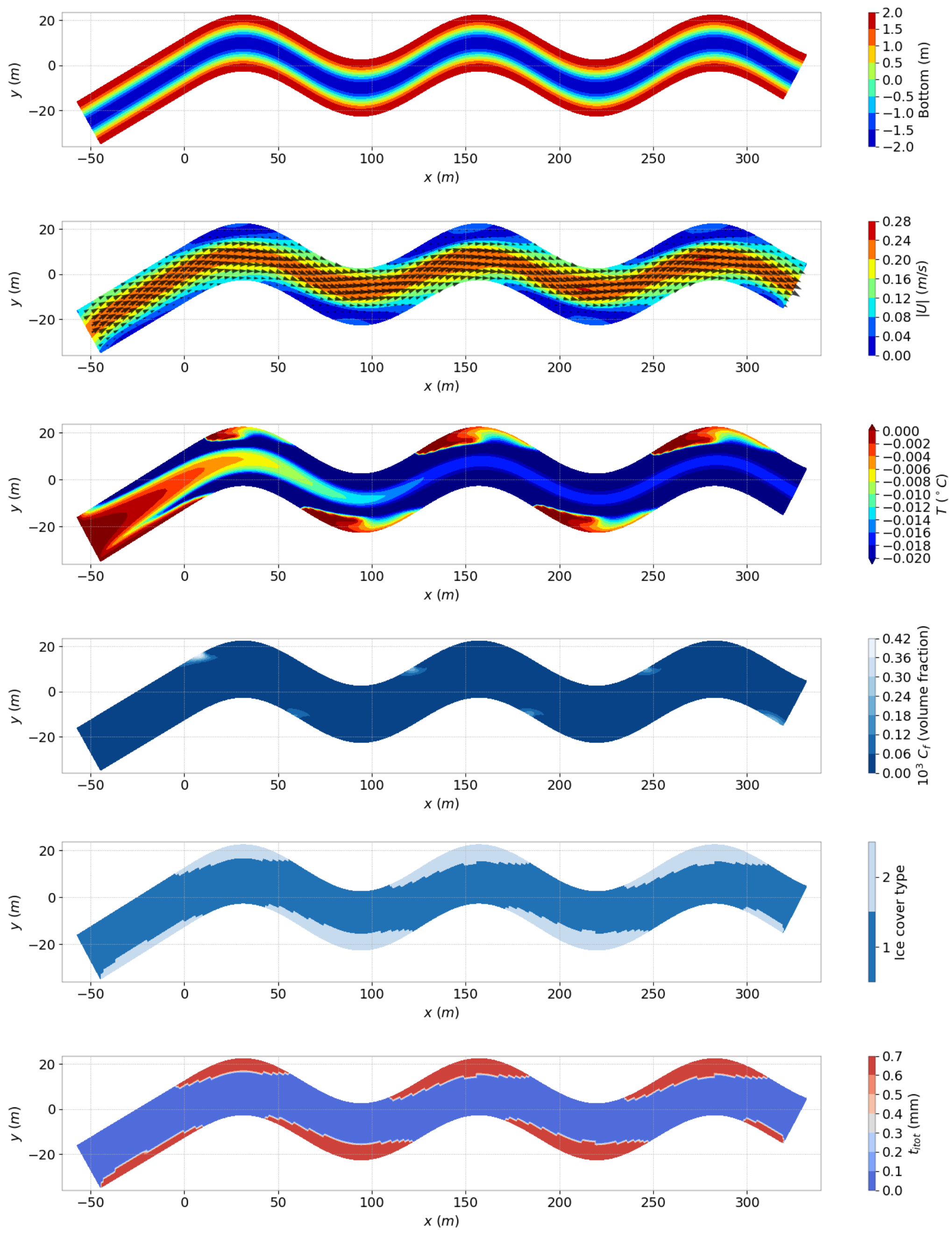



Figure 1.2: Bathymetry, velocity, temperature, frazil volume fraction, surface ice type and ice cover thickness at $t = 15$ minutes

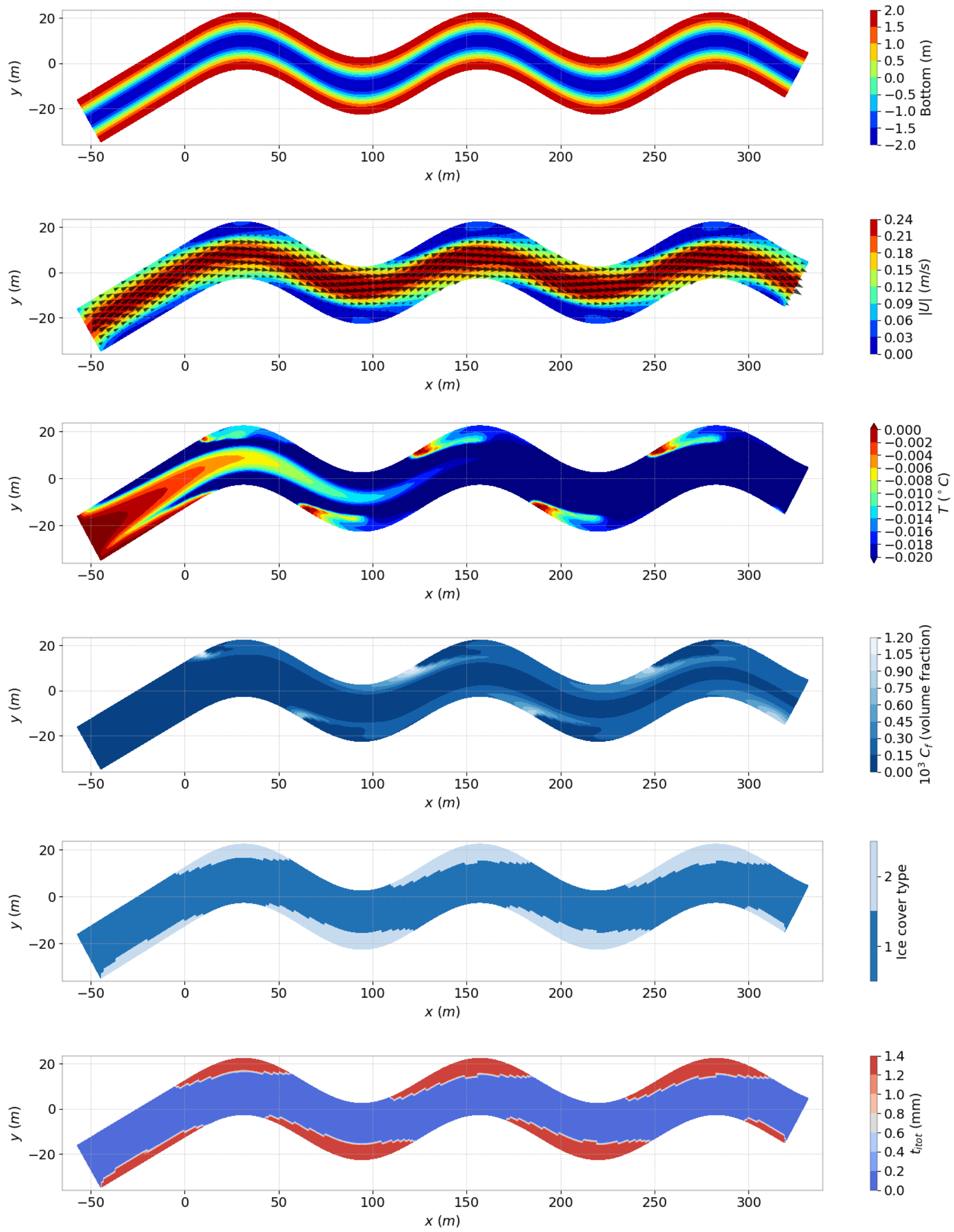



Figure 1.3: Bathymetry, velocity, temperature, frazil volume fraction, surface ice type and ice cover thickness at $t = 30$ minutes

## 1.4 Conclusions

This test case shows the ability of KHIONE to model the formation of border ice along a channel. Once border ice is formed, KHIONE is able to simulate the thermal expansion or decay of the ice cover depending on thermal fluxes on the surface and water temperature. The effect of surface ice has a significant impact on both hydrodynamcis and temperature wich therefore also affect frazil ice formation.

# 2. Clogging of ice on intake racks

## 2.1 Purpose

This test case has been purposefully setup to demonstrate that KHIONE is capable of correctly clogging frazil ice onto the bars of a trash racks.

Accumulation on racks are usually defined at an intake boundary or on a section in the model. In this particular case, the rack is set at the downstream end of a slow moving flume, 10 [km] long at a gentle slope of 1:100,000.

## 2.2 Description

### 2.2.1 Domain

The domain is a long flat-bottom flume, boxed within (0;0) and (150;10,000), its length being 10 [km] along the x-axis and its width being 150 [m] along the y-axis. The channel has a slope of 1:100,000 between the elevation 4.1 [m] (upstream) and 4.0 [m] (downstream).

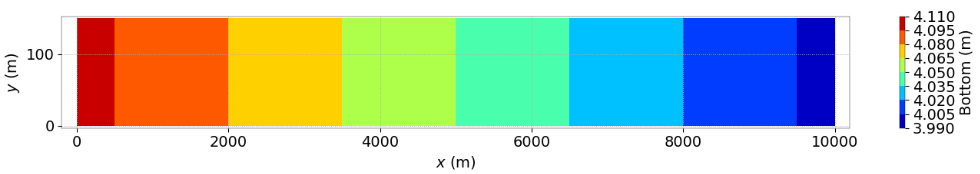



Figure 2.1: Bottom elevation.

### 2.2.2 Mesh

The mesh of the domain was created as a triangulated regular grid with a uniform density of about 0.35 m, resulting in a mesh with 4,800 elements and 2,807 vertices. (see figure 2.2).

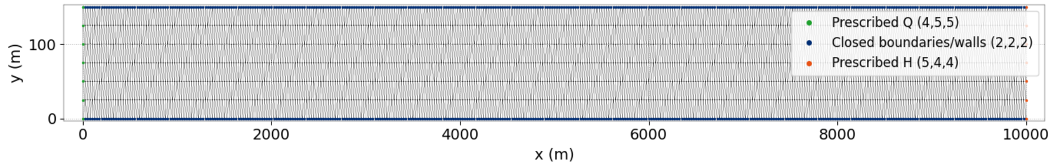



Figure 2.2: Domain mesh.

### 2.2.3 Boundary definitions

There are two solid boundaries and 2 open boundaries.

The solid boundaries are on either side of the length of the flume, considered as solid walls with perfect slip conditions (condition 2 2 2). The open boundaries are at (x=0) for the upstream and at (x=10,0000) for the downstream of the flume. A constant discharge of 30 [$m^3$/s] is imposed at the upstream boundary. A constant water level is set at 6.6265 [m] at the downstream boundary.

In the follow-up simulation, water temperature is entering the domain at 0.1 $°C$. Frazil concentration is set at 0 [SI]. At that temperature, frazil starts growing about 1.5 [km] down the length of the flume.

### 2.2.4 Initial conditions

An initial depth of 3.535 [m] is set for all four variations of the test case. The free surface is subsequently corrected by KHIONE to account for the initial ice cover thickness, as read from the previous ice cover computation file.

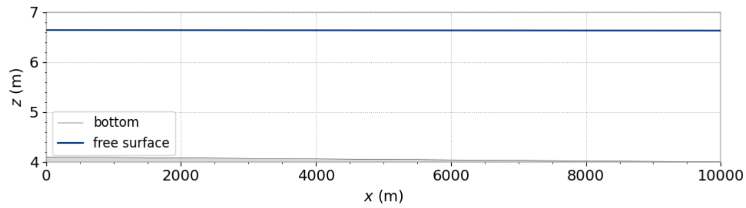



Figure 2.3: Profile of steady state conditions.

Subsequently, temperature and frazil concentration are added in a follow-up simulation.

### 2.2.5 Coupling

The follow-up simulation calls on the thermal exchanges between the atmosphere and the water as computed within KHIONE. The simulation is, therefore, coupled with KHIONE.

- ▷ *COUPLING WITH = 'KHIONE'*
- ▷ *CLOGGING ON BARS = YES*, both thermal budget (by default) and clogging processes are activated within KHIONE

### 2.2.6 Physical parameters

Physical properties are set through three steering files, for which TELEMAC-2 D is coupled with KHIONE.
A friction law is used based on the Manning coefficient:

- ▷ *LAW OF BOTTOM FRICTION = 4*
- ▷ *FRICTION COEFFICIENT = 0.025*

In relation to KHIONE (within the KHIONE steering file), the following physical properties are set for the thermal budget model:

- ▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*
- ▷ *AIR TEMPERATURE = -2.5*

The clogging model is set with the following parameters:

- ▷ *CLOGGED BOUNDARY NUMBER = 1*, means that the boundary number 1, here the downstream boundary, will be clogged;
- ▷ *POROSITY OF ACCUMULATED ICE = 0.67*, when accumulating, porosity is formed in the ice deposited on the rack, which makes its extent larger than the total volume involved in the clogging process;
- ▷ *ANGLE OF ACCUMULATED ICE = 35.*,
- ▷ *PHYSICAL CHARACTERISTICS OF THE INTAKE RACK = 0.2; 0.00; 0.2;0.01*, indicates the distance between the cross bars and their diameter, then the distance between the vertical bars and their diameter. Here, as the diameter of the cross bars is zero, the grid is considered to have only vertical bars, with a diameter of 1 cm and separated from each other by 20 cm.

The figure 2.4 illustrates the meaning of the angle of accumulated ice $\theta$, and the physical properties of the racks.

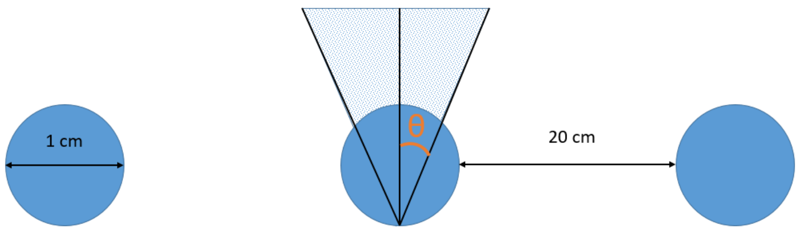



Figure 2.4: Illustration of the physical parameters used for the clogging.

### 2.2.7 Numerical parameters

Only two numerical parameters are essential to the simulation. These are defined in the TELEMAC-2 D steering file:

- ▷ *TIME STEP = 30.* and

- ▷ *NUMBER OF TIME STEPS = 4320* for the steady state simulation;
- ▷ *TIME STEP = 5.* and
- ▷ *NUMBER OF TIME STEPS = 18000* for the coupled simulation.

## 2.3 Results

The following figure (Figure 2.5) shows a longitudinal profile of water temperature (red) and frazil concentration (blue) along the full length of the flume.

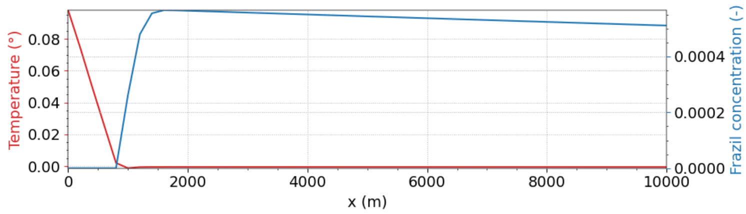



Figure 2.5: Water temperature and frazil growth along the flume.

The figure 2.6 shows the temporal evolution of the avaliable area at the rack and the accumulated volume of frazil on the grid. One can see a quick augmentation of the volume and an associated diminution of the area when the clogging process has started.

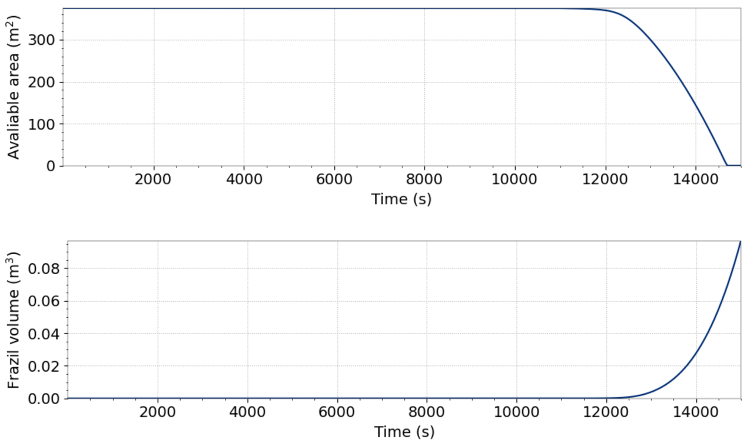



Figure 2.6: Avaliable area and accumulated volume of frazil on the grid.

The model is also able to represent clogging in a section in the middle of the model. The figure 2.7 shows the location of the section representing the grid in the middle of the model and the temporal evolution of the avaliable area at the rack and the accumulated volume of frazil on the grids.

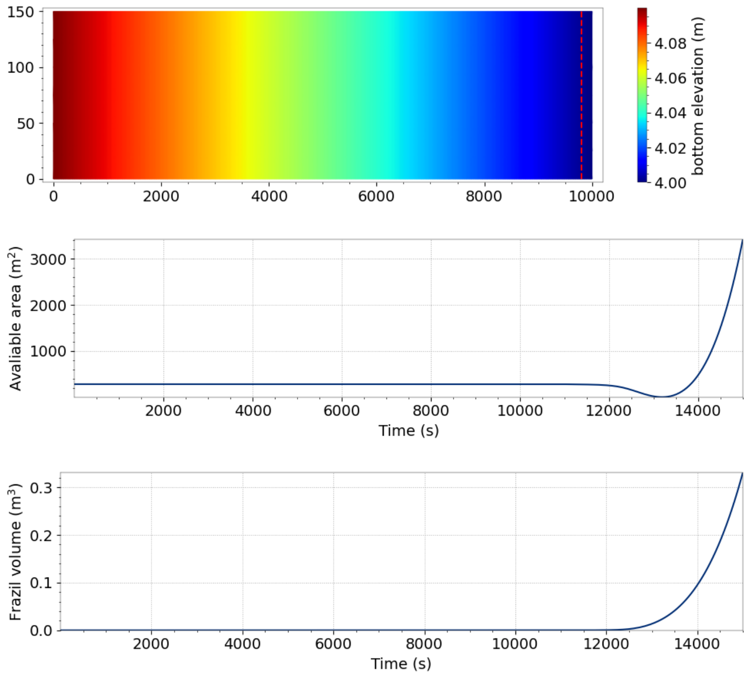



Figure 2.7: Avaliable area and accumulated volume of frazil on the grid given by a section in the model.

## 2.4 Conclusions

Clogging processes have been appropriately modelled to account for the presence of racks at one or more intake boundary.

# 3. Supercooling and frazil ice growth

## 3.1 Purpose

This test case demonstrates that KHIONE is capable of correctly reproduce supercooling and frazil ice growth. Water is running down a flat flume over $10km$ long at a gentle slope of 1:10,000. A linear thermal budget formulation is used with an air temperature set to $-15°C$. At the end of the simulation temperature and frazil ice reach a steady state in the domain. Temperature is decreasing from the inlet to reached a max supercooling temperature of about $-0.02°C$, and then converges towards zero as frazil ice is beeing produced.

## 3.2 Description

### 3.2.1 Geometry, mesh and bathymetry

The domain is a long flat-bottom flume, boxed within $(x = 0, y = 0)$ and $(x = 10,000, y = 150)$, its length being $10km$ along the x-axis and its width being $150m$ along the y-axis. The channel has a slope of 1:10,000 between the elevation $5m$ (upstream) and $4m$ (downstream).

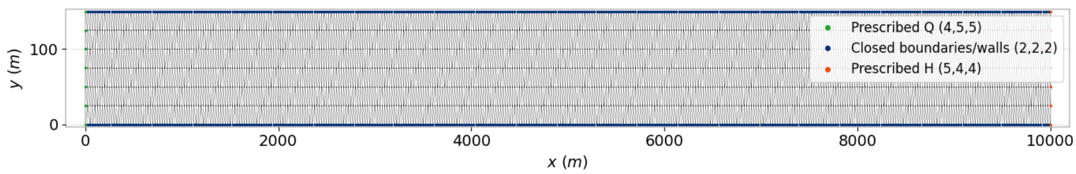



Figure 3.1: Domain mesh

The mesh of the domain was created with a uniform density of about $0.35m$, resulting in a mesh with 4800 elements and 2807 vertices (cf. figure 9.1).

### 3.2.2 Initial conditions

A hydrodynamics steady state condition is established first separately to reach a constant and uniform water depth of $6.6265m$ and a constant and uniform discharge of $300m^3/s$. Water temperature is initially set at $0.05°C$. Initial frazil volume fraction is set to 0. These values are also used for the upstream boundary condition.

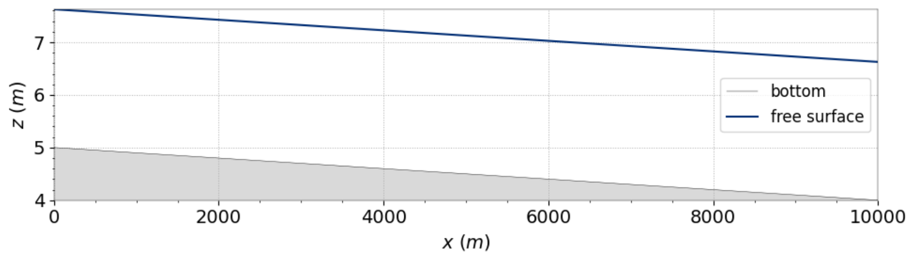



Figure 3.2: Initial elevation profile

### 3.2.3 Boundary conditions

There are two solid boundaries and 2 open boundaries. The solid boundaries are on either side of the length of the flume, considered as solid walls with perfect slip conditions. The open boundaries are at $(x = 0)$ for the upstream and at $(x = 10,000)$ for the downstream of the flume. A constant discharge of $300m^3/s$ is imposed at the upstream boundary with a temperature set to $0.05°C$. A constant water level is set at $6.6265m$ at the downstream boundary. A first simulation is carried out with for the hydrodynamics only to get to a steady state equilibrium of a constant and uniform water depth of $6.6265m$ and a constant and uniform discharge of $300m^3/s$ along the entire length of the flume.

### 3.2.4 Atmospheric drivers

For this test case, linear heat exchanges are used i.e. within the KHIONE steering file:

- ▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi^* = \phi_R + \alpha + \beta(T_{air} - T_{water}) \tag{3.1}$$

where $\phi_R$ the net solar radiation flux, which depends on the solar constant $I_{so}$ and the latitude but also atmospheric properties like the nebulosity and the visibility. $\alpha$ and $\beta$ are two coefficient that are set to $-50W.m^{-2}$ and $20W.m^{-2}.K^{-1}$ by default. $I_{so}$, $\alpha$ and $\beta$ are adjusted within the KHIONE steering file:

- ▷ *SOLAR CONSTANT = 0.*
- ▷ *WATER-AIR HEAT EXCHANGE CONSTANT = 0.*
- ▷ *WATER-AIR HEAT EXCHANGE COEFFICIENT = 20.*

Air temperature is set to a constant during the simulation:

- ▷ *AIR TEMPERATURE = -15.0*

### 3.2.5 Physical parameters

In order to balance the slope and the discharge through the flume, a Manning friction law is used, with a coefficient of 0.025.
Physical properties related to frazil growth rate are defined in the KHIONE steering file. Let us recall the expression of the frazil thermal growth source term i.e. $S_{GM}$:

$$S_{GM} = \frac{q a_0 N}{\rho_i L_i} \tag{3.2}$$

where $a_0$ is the surface area of frazil particles normal to the a-axis, $N$ is the number of frazil crystals per unit volume, $\rho_i$ the density of ice, $L_i$ the latent heat of fusion and $q$ the heat transfert rate defined by:

$$q = \frac{K_w N_u}{l}(T_f - T) \tag{3.3}$$

with $N_u$ the Nusselt number, $l$ is the characteristic length scale of the thermal boundary layer around frazil ice particles, supposed to be equal to the thickness, $K_w$ the thermal conductivity of water and $T_f$ the fusion temperature. Note that $a_0$ is defined by $a_0 = 2\pi re$ with $r$ the radius of frazil ice granules. In KHIONE $e$ is defined such that $2r/e = R$ where $R$ is a user defined ratio (set to 8 by default). The number of particule per unit volume is defined by $N = C/V_0$ with $V_0 = \pi er^2$ and $C$ the volume fraction of frazil ice. In this test case, $N_u$, $r$, $R$ are defined with their default values:

- ▷ *NUSSELT NUMBER = 4.*
- ▷ *FRAZIL CRYSTALS RADIUS = 4.1E-4*
- ▷ *FRAZIL CRYSTALS DIAMETER THICKNESS RATIO = 10.*

### 3.2.6 Numerical parameters

The time step is set to $2s$ and the number of timestep is set to 18000 which leads to a simulation time of $24h$.

## 3.3 Results

The figures 5.3 and 3.4 show the temperature and the frazil concentration along the flume at different times. Steady state is reached after only several hours of simulation.

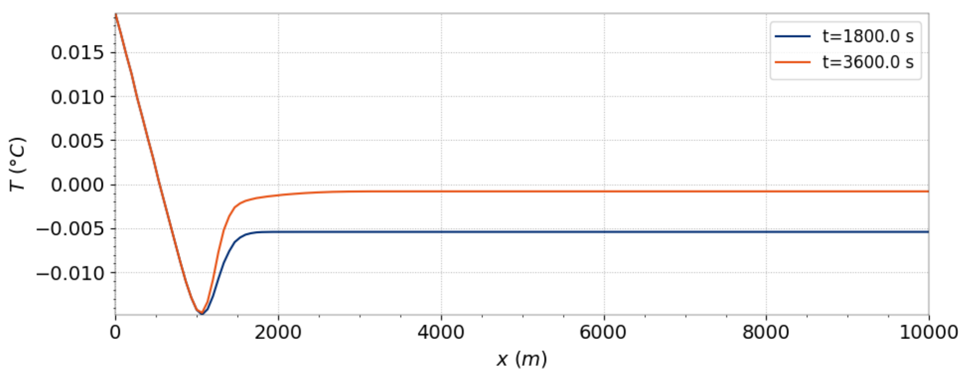



Figure 3.3: Water temperature along the flume

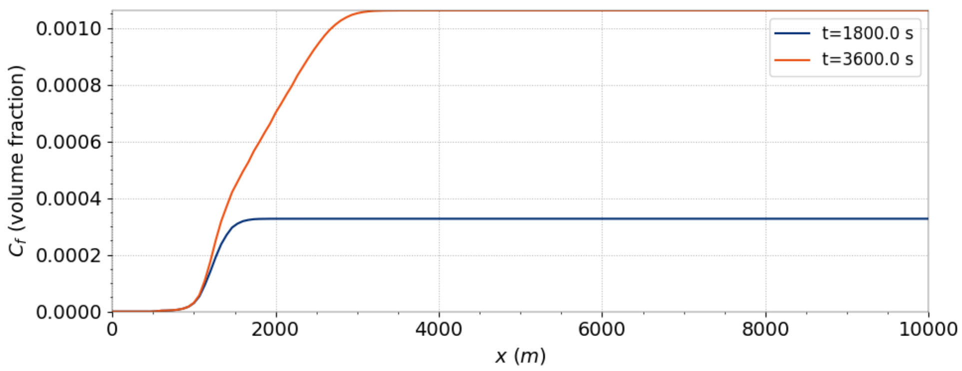



Figure 3.4: Frazil ice concentration along the flume

On figures 5.6 and 5.5 the frazil concentration and temperature are plotted along the flume at final time. On figure 5.7 the evolution of frazil and temperature against time is plotted for the point (x=9000, y=75) located near the end of the flume.

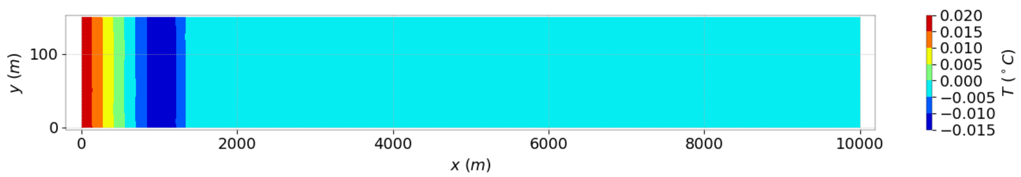



Figure 3.5: Water temperature along the flume at final time

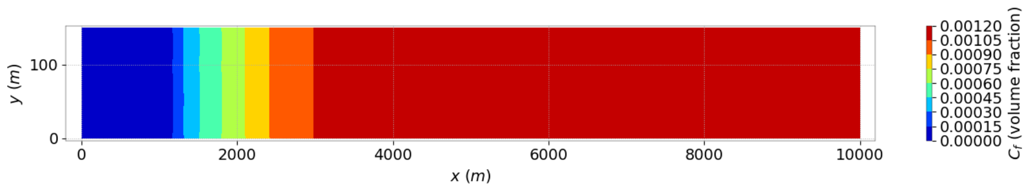



Figure 3.6: Frazil ice concentration along the flume at final time

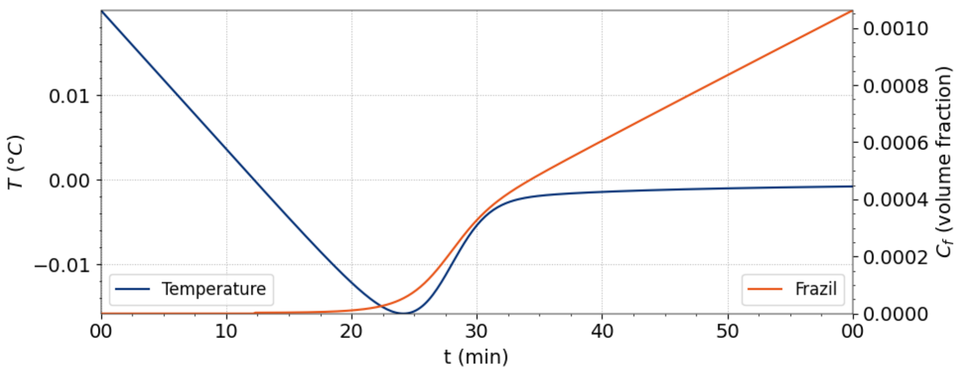



Figure 3.7: Water temperature and frazil growth against time at ($x = 9000$, $y = 75$)

As the water temperature goes below $0°C$, the creation of frazil floes cools down the water temperature further to a super-cool temperature. In turn, further growth of frazil ice release latent heat, which heats up again water to a temperature just below $0°C$.

## 3.4 Conclusions

The variation in water temperature over the length of the flume highlights the process of thermal growth of the frazil ice with a long exposure to cold air temperature. Coming in the flume at a temperature slightly above zero, the longer water is exposed to the cold air temperature the cooler (or super-cooler) it gets until frazil floes starts to appear.

# 4. Supercooling and frazil ice growth - 3D

## 4.1 Purpose

This test case demonstrates that KHIONE is capable of correctly reproduce supercooling and frazil ice growth in 3D. Water is running down a flat flume over 10 km long at a gentle slope of 1:10,000. A linear thermal budget formulation is used with an air temperature set to -15°C. At the end of the simulation temperature and frazil ice reach a steady state in the domain. Temperature is decreasing from the inlet to reached a max supercooling temperature of about -0.02°C, and then converges towards zero as frazil ice is beeing produced.

## 4.2 Description

### 4.2.1 Geometry, mesh and bathymetry

The domain is a long flat-bottom flume, boxed within $(x = 0, y = 0)$ and $(x = 10,000, y = 150)$, its length being 10 km along the x-axis and its width being 150 m along the y-axis. The channel has a slope of 1:10,000 between the elevation 5 m (upstream) and 4 m (downstream).

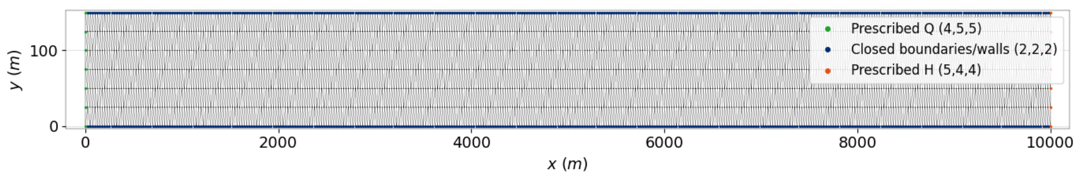



Figure 4.1: Domain mesh

The mesh of the domain was created with a uniform density of about 0.35 m, resulting in a mesh with 4800 elements and 2807 vertices (cf. figure 9.1). The number of plane in the vertical dimension is 5.

### 4.2.2 Initial conditions

A hydrodynamics steady state condition is established first separately to reach a constant and uniform water depth of 6.6265 m and a constant and uniform discharge of 300 $m^3/s$. Water temperature is initially set at 0.02°C. Initial frazil volume fraction is set to 0. These values are also used for the upstream boundary condition.

### 4.2.3 Boundary conditions

There are two solid boundaries and 2 open boundaries. The solid boundaries are on either side of the length of the flume, considered as solid walls with perfect slip conditions. The open boundaries are at $(x = 0)$ for the upstream and at $(x = 10,000)$ for the downstream of the flume. A constant discharge of 300 $m^3$/s is imposed at the upstream boundary with a temperature set to 0.02°C. A constant water level is set at 6.6265 m at the downstream boundary. A first simulation is carried out with for the hydrodynamics only to get to a steady state equilibrium of a constant and uniform water depth of $6.6265m$ and a constant and uniform discharge of $300m^3/s$ along the entire length of the flume.

### 4.2.4 Atmospheric drivers

For this test case, linear heat exchanges are used i.e. within the KHIONE steering file:

▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi^* = \phi_R + \alpha + \beta(T_{air} - T_{water}) \tag{4.1}$$

where $\phi_R$ the net solar radiation flux, which depends on the solar constant $I_{so}$ and the latitude but also atmospheric properties like the nebulosity and the visibility. $\alpha$ and $\beta$ are two coefficient that are set to $-50$ W.m$^{-2}$ and 20 W.m$^{-2}$.K$^{-1}$ by default. $I_{so}$, $\alpha$ and $\beta$ are adjusted within the KHIONE steering file:

▷ *SOLAR CONSTANT = 0.*

▷ *WATER-AIR HEAT EXCHANGE CONSTANT = 0.*

▷ *WATER-AIR HEAT EXCHANGE COEFFICIENT = 20.*

Air temperature is set to a constant during the simulation:

▷ *AIR TEMPERATURE = -15.0*

### 4.2.5 Physical parameters

In order to balance the slope and the discharge through the flume, a Manning friction law is used, with a coefficient of 0.025.
Physical properties related to frazil growth rate are defined in the KHIONE steering file. Let us recall the expression of the frazil thermal growth source term i.e. $S_{GM}$:

$$S_{GM} = \frac{q a_0 N}{\rho_i L_i} \tag{4.2}$$

where $a_0$ is the surface area of frazil particles normal to the a-axis, $N$ is the number of frazil crystals per unit volume, $\rho_i$ the density of ice, $L_i$ the latent heat of fusion and $q$ the heat transfert rate defined by:

$$q = \frac{K_w N_u}{l}(T_f - T) \tag{4.3}$$

with $N_u$ the Nusselt number, $l$ is the characteristic length scale of frazil ice particules, supposed to be equal to the radius, $K_w$ the thermal conductivity of water and $T_f$ the fusion temperature. Note that $a_0$ is defined by $a_0 = 2\pi re$ with $r$ the radius of frazil ice granules. In KHIONE $e$ is defined such that $2r/e = R$ where $R$ is a user defined ratio (set to 8 by default). The number of particule per unit volume is defined by $N = C/V_0$ with $V_0 = \pi er^2$ and $C$ the volume fraction of frazil ice. In this test case, $N_u$, $r$, $R$ are defined with their default values:

▷ *NUSSELT NUMBER = 4.*

▷ *FRAZIL CRYSTALS RADIUS = 1.2E-4*

▷ *FRAZIL CRYSTALS DIAMETER THICKNESS RATIO = 10.*

### 4.2.6 Numerical parameters

The time step is set to 1 s and the number of timestep is set to 3600 which leads to a simulation time of 1 h.

## 4.3 Results

On figures 5.6 and 5.5 the frazil concentration and temperature are plotted along the flume at final time. Figure 4.4 and 4.5 show the surface layer concentration of frazil and temperature. One can note that the formation of the frazil mainly occurs on the top layer, since its concentration is about 10 time higher than the mean vertical concentration.

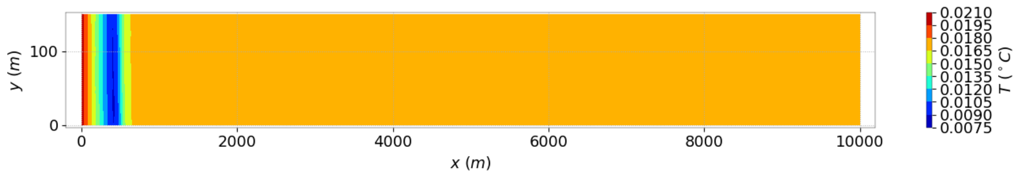



Figure 4.2: Water temperature along the flume at final time, vertical averaging

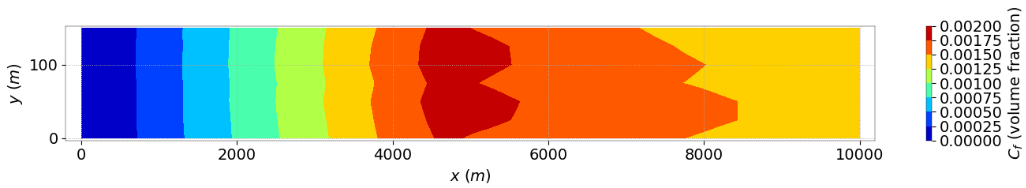



Figure 4.3: Frazil ice concentration along the flume at final time, vertical averaging

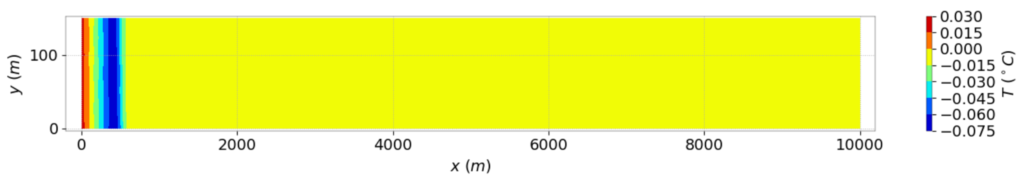



Figure 4.4: Water temperature along the flume at final time, surface plane

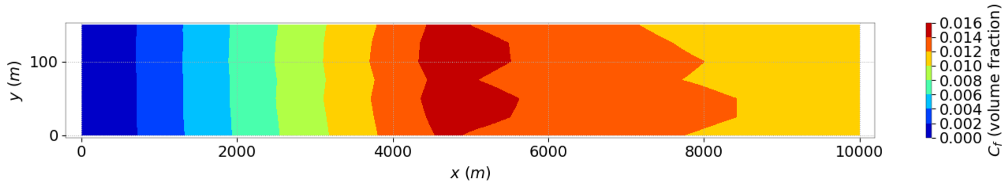



Figure 4.5: Frazil ice concentration along the flume at final time, surface plane

The figure 4.6 shows the impact the water salinity on the melting point.

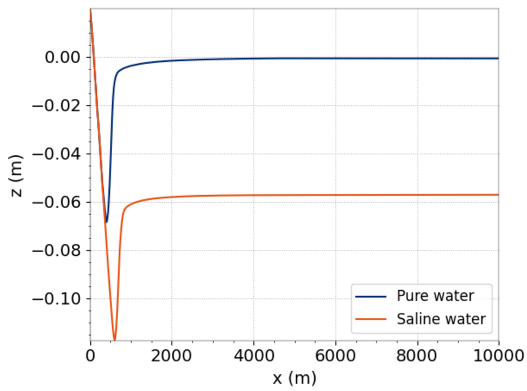



Figure 4.6: Temperature along the channel at the final time, when the water is salted or not

As the water temperature goes below 0 °C, the creation of frazil floes cools down the water temperature further to a super-cool temperature. In turn, further growth of frazil ice release latent heat, which heats up again water to a temperature just below 0 °C.

## 4.4 Conclusions

The variation in water temperature over the length of the flume highlights the process of thermal growth of the frazil ice with a long exposure to cold air temperature. Coming in the flume at a temperature slightly above zero, the longer water is exposed to the cold air temperature the cooler (or super-cooler) it gets until frazil floes starts to appear.

# 5. Supercooling and frazil ice growth in a trapezoidal flume

## 5.1 Purpose

This test case demonstrates that KHIONE is capable of correctly reproduce supercooling and frazil ice growth in presence of dry/wet interfaces. Water is running down a trapezoidal flume over 400 m long at a gentle slope of 5:10,000. A linear thermal budget formulation is used with an air temperature set to $-15°C$. At the end of the simulation temperature and frazil ice reach a steady state in the domain.

## 5.2 Description

### 5.2.1 Geometry, mesh and bathymetry

The domain is a long trapezoidal flume, boxed within $(x = 0, y = 0)$ and $(x = 400, y = 36)$, its length being 400 m along the x-axis and its width being 36 m along the y-axis. The channel has a slope of 5:10,000 between the elevation 0.2 m (upstream) and 0 m (downstream).

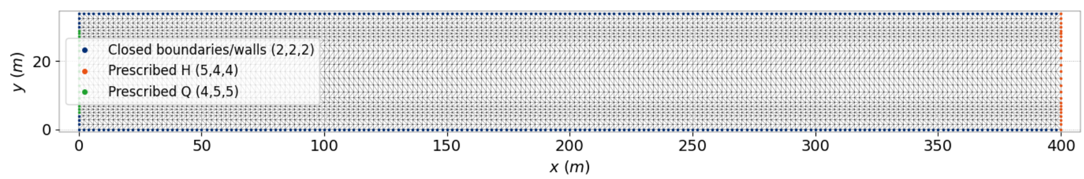



Figure 5.1: Domain mesh

### 5.2.2 Initial conditions

A hydrodynamics steady state condition is established first separately to reach a constant and uniform water depth of 1.75 m in the middle of the section and a constant and uniform discharge of 30.38m$^3$/s. Water temperature is initially set at $0°C$. Initial frazil volume fraction is set to 0. These values are also used for the upstream boundary condition.

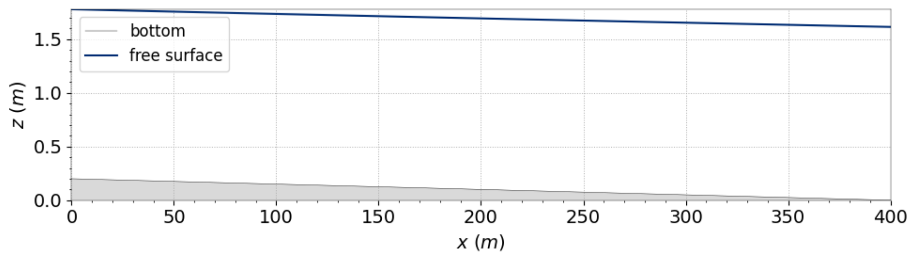



Figure 5.2: Initial elevation profile

### 5.2.3 Boundary conditions

There are two solid boundaries and 2 open boundaries. The solid boundaries are on either side of the length of the flume, considered as solid walls with perfect slip conditions. The open boundaries are at $(x = 0)$ for the upstream and at $(x = 400)$ for the downstream of the flume. A constant discharge of 30.38m$^3$/s is imposed at the upstream boundary with a temperature set to $0°C$. A constant water level is set at $1.6154m$ at the downstream boundary. A first simulation is carried out with for the hydrodynamics only to get to a steady state equilibrium of a constant and uniform water depth of $1.6154m$ and a constant and uniform discharge of $300m^3/s$ along the entire length of the flume.

### 5.2.4 Atmospheric drivers

For this test case, linear heat exchanges are used i.e. within the KHIONE steering file:

▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi^* = \phi_R + \alpha + \beta(T_{air} - T_{water}) \tag{5.1}$$

where $\phi_R$ the net solar radiation flux, which depends on the solar constant $I_{so}$ and the latitude but also atmospheric properties like the nebulosity and the visibility. $\alpha$ and $\beta$ are two coefficient that are set to $-50W.m^{-2}$ and $20W.m^{-2}.K^{-1}$ by default. Air temperature is set to a constant during the simulation:

▷ *AIR TEMPERATURE = -15.0*

### 5.2.5 Physical parameters

In order to balance the slope and the discharge through the flume, a Manning friction law is used, with a coefficient of 0.025.
Physical properties related to frazil growth rate are defined in the KHIONE steering file. In this test case, $N_u$, $r$, $R$ are defined with their default values i.e.

▷ *NUSSELT NUMBER = 4.*

▷ *FRAZIL CRYSTALS RADIUS = 1.2E-4*

▷ *FRAZIL CRYSTALS DIAMETER THICKNESS RATIO = 10.*

### 5.2.6 Numerical parameters

The time step is set to $0.5s$ and the number of timestep is set to 7200 which leads to a simulation time of $1h$.

## 5.3 Results

The figure 5.3 show the temperature and the frazil volume fraction the centerline of the flume at final time. The figure 5.4 show the temperature and the frazil volume fraction the right bank of the flume at final time.

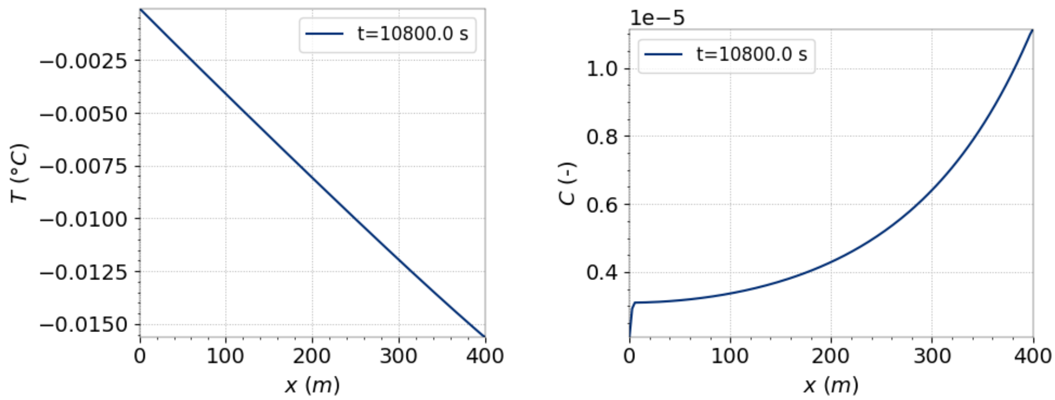



Figure 5.3: Water temperature (left) and frazil volume fraction (right) along the centerline of the flume (y=36)

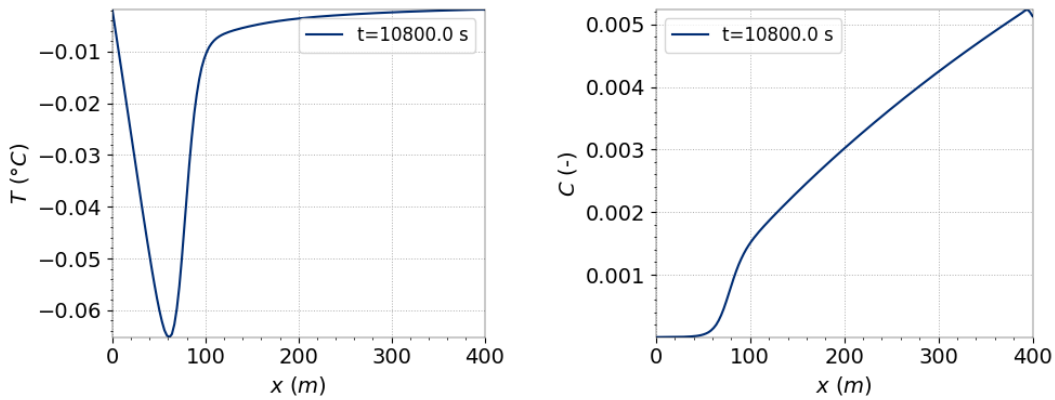



Figure 5.4: Water temperature (left) and frazil volume fraction (right) along the right bank of the flume (y=5)

On figures 5.6 and 5.5 the frazil concentration and temperature are plotted along the flume at final time.

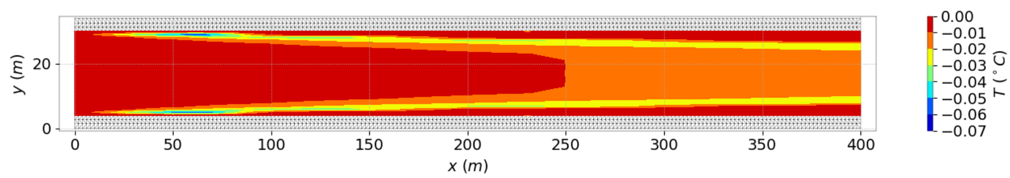



Figure 5.5: Water temperature along the flume at final time

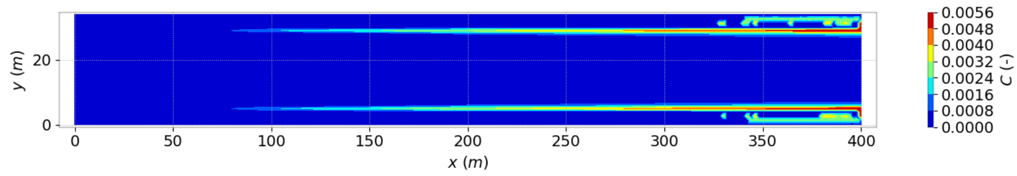



Figure 5.6: Frazil ice concentration along the flume at final time

The figure 5.7 show the temperature and the frazil volume fraction against time the centerline of the flume at final time. The figure 5.8 show the temperature and the frazil volume fraction against time the right bank of the flume at final time.

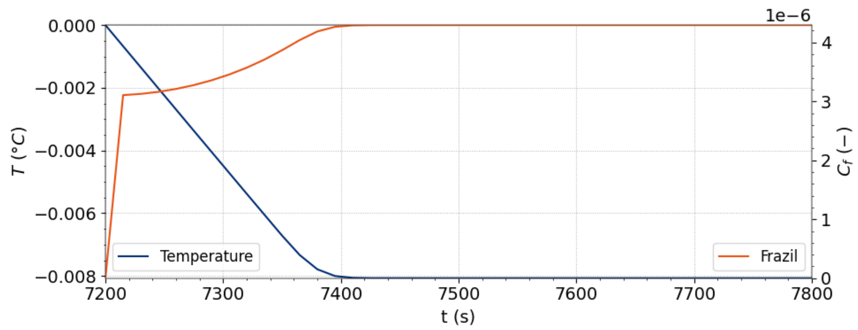



Figure 5.7: Water temperature and frazil growth against time at $(x = 200, y = 18)$

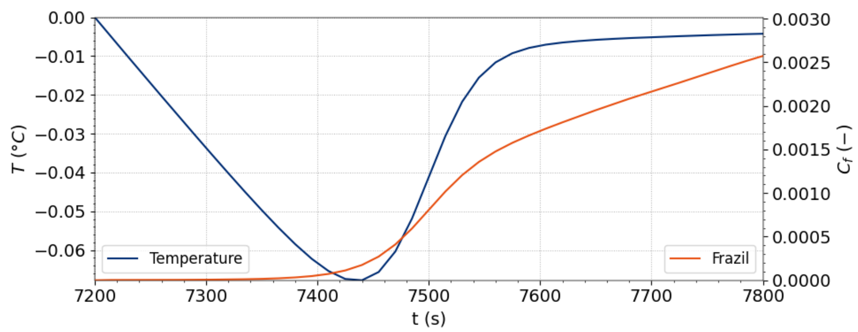



Figure 5.8: Water temperature and frazil growth against time at $(x = 200, y = 5)$

## 5.4 Conclusions

This test case highlights the heterogeneity of frazil ice growth depending on water depth. At constant air temperature, lower water depth increases the volumetric cooling rate of water, leading to a quicker frazil ice growth dynamic.

# 6. Presence of ice cover

## 6.1 Purpose

This test case has been purposefully setup to demonstrate that KHIONE is capable of correctly modify the hydrodynamics to account for the presence of an ice cover. Four variations of the same test case are shown here, where different ice cover conditions are set through made-up previous ice cover computation file. Water is running down a flat flume over 10km long at a gentle slope of 1:10,000. It should be noted that the heat exchange processes are not included. As a result, the tracers (temperature and frazil concentrations) are not activated and the initial ice cover remains unchanged throughout the simulation.

## 6.2 Description

### 6.2.1 Geometry, mesh and bathymetry

The domain is a long flat-bottom flume, boxed within (0;0) and (150;10,000), its length being 10km along the x-axis and its width being 150m along the y-axis. The channel has a slope of 1:10,000 between the elevation 5m (upstream) and 4m (downstream). The mesh of the domain was created as a triangulated regular grid with a uniform density of about 0.35 m, resulting in a mesh with 4,800 elements and 2,807 vertices. (see figure 6.1).

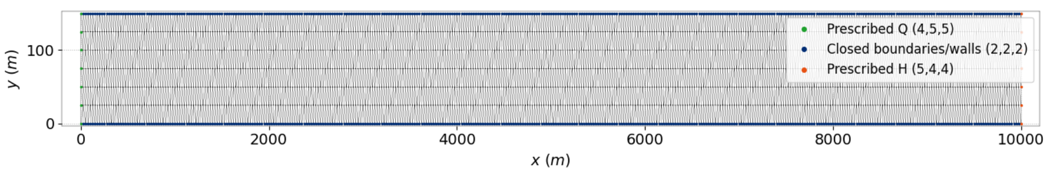



Figure 6.1: Domain mesh

### 6.2.2 Initial conditions

A first simulation is carried out for the hydrodynamics only to get to a steady state equilibrium. An initial depth of 3.535m is set for all four variations of the test case. The free surface is subsequently corrected by KHIONE to account for the initial ice cover thickness, as read from the previous ice cover computation file.

### Uniform ice cover

The first variation of the test case is set with a uniform ice cover throughout the length of the channel.

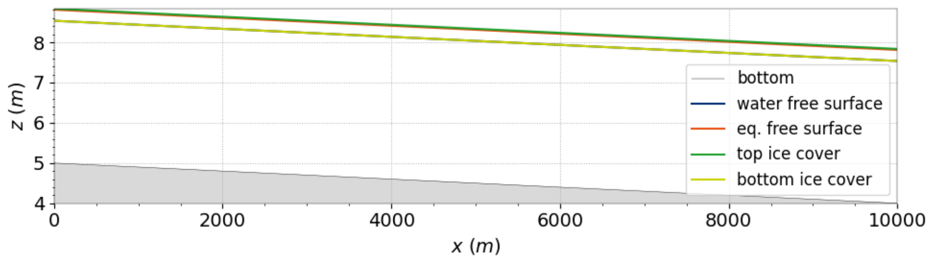



Figure 6.2: Initial ice cover

### Downstream ice cover

The second variation is set with only a partial cover of uniform thickness, on the downstream part 4 [km] from the upstream boundary.

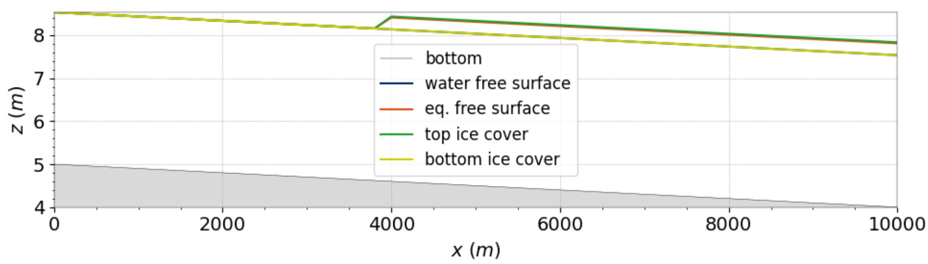



Figure 6.3: Initial ice cover

### Upstream ice cover

The third test case is also set with a partial ice cover but on the upstream part 4 [km] of the channel.

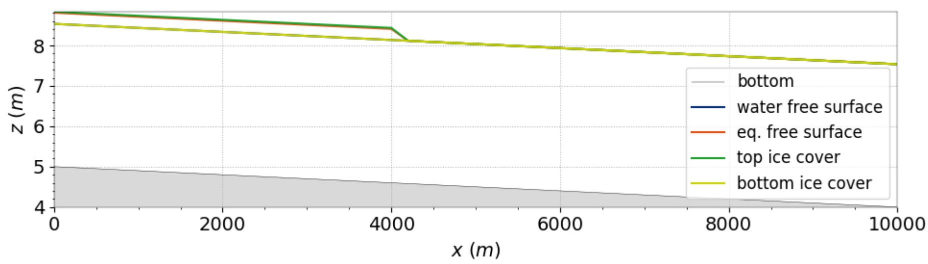



Figure 6.4: Initial ice cover

### Representative ice jam

Last but not least, the fourth variation of the test case is set with an ice jam, with an ice thickness varying along the length of the channel. The following figure (Figure 6.5) shows coloured contours of the chosen ice thickness for each test case variation.

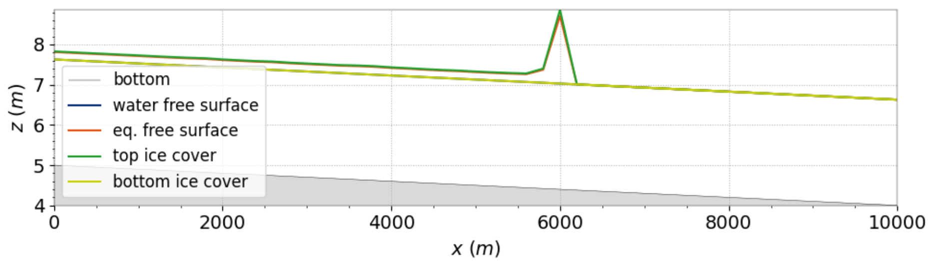



Figure 6.5: Initial ice cover

It is noted that ice thickness x ice density = water layer thickness x water density.

### 6.2.3 Boundary definitions

There are two solid boundaries and 2 open boundaries. The solid boundaries are on either side of the length of the flume, considered as solid walls with perfect slip conditions (condition 2 2 2). The open boundaries are at (x=0) for the upstream and at (x=10,0000) for the downstream of the flume. A constant discharge of $300m^3/s$ is imposed at the upstream boundary. A constant water level is set at $7.535m$ at the downstream boundary.

### 6.2.4 Physical parameters

In order to balance the slope and the discharge through the flume, a Manning friction law is used, with a coefficient of 0.025 (within the TELEMAC-2 D steering file).
Note that when ice cover is present, the flow can't be considered as a free surface flow anymore. This is a strong limitation that has not been overcome due to the complexity of modifying the shallow water equations to properly model constrained flows. Instead, hydrostatic assumption is still considered and the effect of ice is taken into account as a static air pressure acting on the surface. Thus, air pressure needs to be activated within the TELEMAC-2 d steering file in order to take the effect of the ice cover on the pressure into account i.e.

- ▷ *AIR PRESSURE = YES*

The second important effect of ice cover onto hydrodynamics is the under cover friction source term. It is taken into account via the following keywords in the KHIONE steering file:

- ▷ *LAW OF ICE COVER FRICTION = 4*
- ▷ *FRICTION COEFFICIENT = 0.02*

Note that the friction law selected for the ice under cover is independant of the one used for the bottom. In this case, we have chosen a Manning friction law, with a under-cover roughness of 0.02. When no additionnal keywords are provided, the friction coefficient is considered constant. It is also possible to increase linearly the roughness with the thickness of the ice cover with the keyword *LAW FOR FRICTION COEFFICIENT* = 1 (default = 0). The effective roughness coefficient becomes:

$$n_{eff} = \frac{t_i n}{t_{ic}}, \tag{6.1}$$

with $t_i$ the ice cover thickness (in $m$), $t_{ic}$ the critical ice thickness (in $m$) which can be set with the keyword *EQUIVALENT SURFACE ICE THICKNESS* (default = 0.001). The the range $n_{eff}$

is kept between the prescribed value of $n$ and a value of $n_{max}$ set with the keyword *MAXIMAL FRICTION COEFFICIENT*. This formula is only usable with a Manning friction law.
For each of the four cases, two runs are made with different under cover friction models. The first model computes the under cover friction with a Manning law on the entire water column, the second computes ratios of the depth affected by the ice friction and the bottom friction. These are controled by the keyword *MODEL FOR UNDER COVER FRICTION*.

### 6.2.5 Numerical parameters

Only two numerical parameters are essential to the simulation. These are defined in the TELEMAC-2 D steering file:

- ▷ *TIME STEP = 5.*
- ▷ *NUMBER OF TIME STEPS = 7200*

The total duration of the simulation is, therefore, 10 hours.

## 6.3 Results

### 6.3.1 Uniform ice cover

Once steady state is reached, longitudinal cross sectional profiles are extracted from the results for the free surface (completely under the ice) and the ice cover. Figure 6.6 shows the results with the total friction law and figure 6.7 shows the figure with the ratio based law.

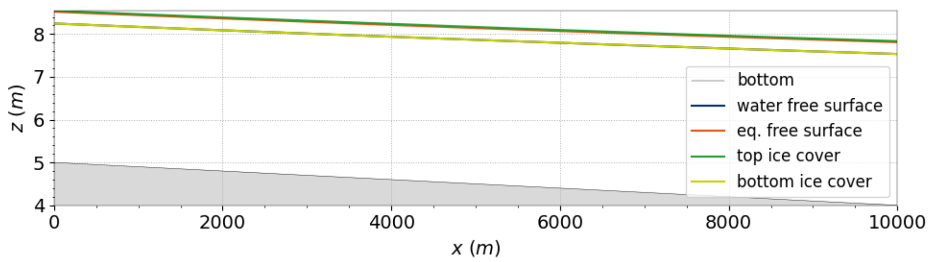



Figure 6.6: Resulting free surface and ice cover

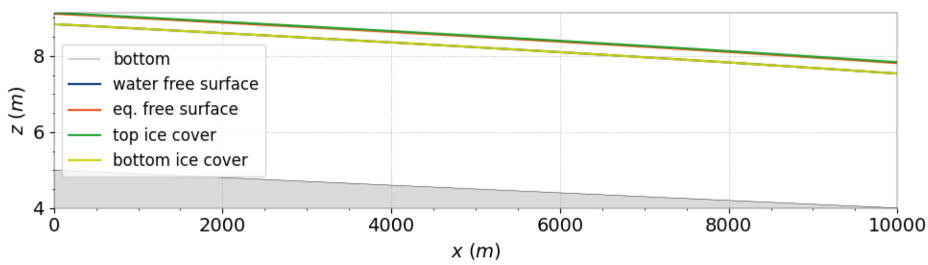



Figure 6.7: Resulting free surface and ice cover

It is noted that, while the upstream boundary is a discharge boundary, the imposed level at the downstream boundary (less the ice cover thickness at the downstream boundary) sets the water level in the domain.

### 6.3.2 Downstream ice cover

Once steady state is reached, longitudinal cross sectional profiles are extracted from the results for the free surface (partially under the ice) and the ice cover. Figure 6.8 shows the results with the total friction law and figure 6.9 shows the figure with the ratio based law.

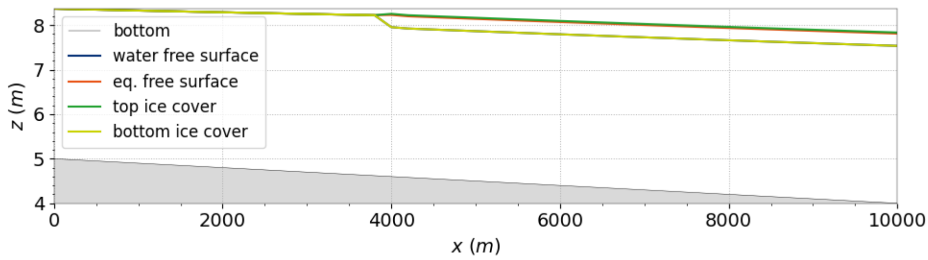



Figure 6.8: Resulting free surface and ice cover

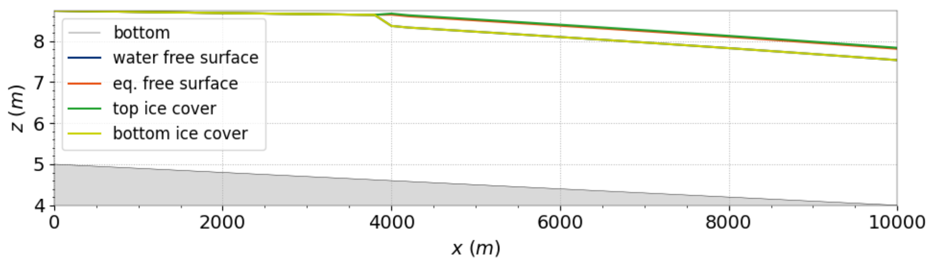



Figure 6.9: Resulting free surface and ice cover

Again, the imposed level at the downstream boundary (less the ice cover thickness at the downstream boundary) sets the water level in the domain.

### 6.3.3 Upstream ice cover

Once steady state is reached, longitudinal cross sectional profiles are extracted from the results for the free surface (partially under the ice) and the ice cover. Figure 6.10 shows the results with the total friction law and figure 6.11 shows the figure with the ratio based law.

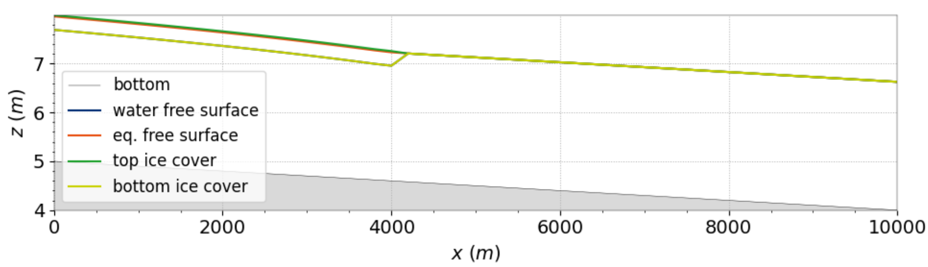



Figure 6.10: Resulting free surface and ice cover

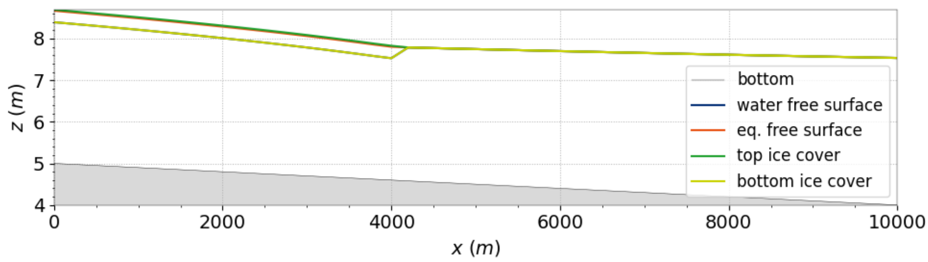



Figure 6.11: Resulting free surface and ice cover

In this case, the water is free of ice on the downstream side, and the water is therefore set directly by the user.

### 6.3.4 Representative ice jam

Similarly, once steady state is reached, longitudinal cross sectional profiles are extracted from the results for the free surface (in the presence of an ice jam) and the ice cover. Figure 6.12 shows the results with the total friction law and figure 6.13 shows the figure with the ratio based law.

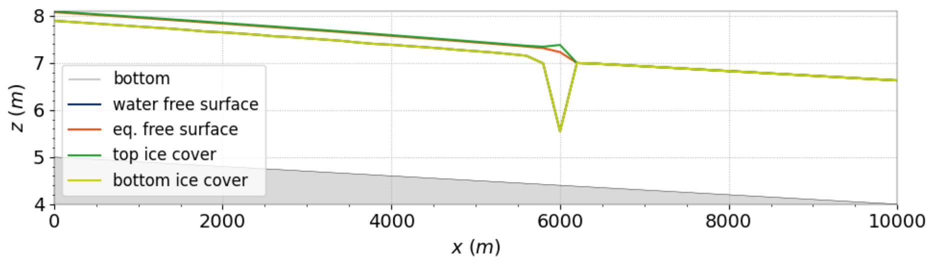



Figure 6.12: Resulting free surface and ice cover

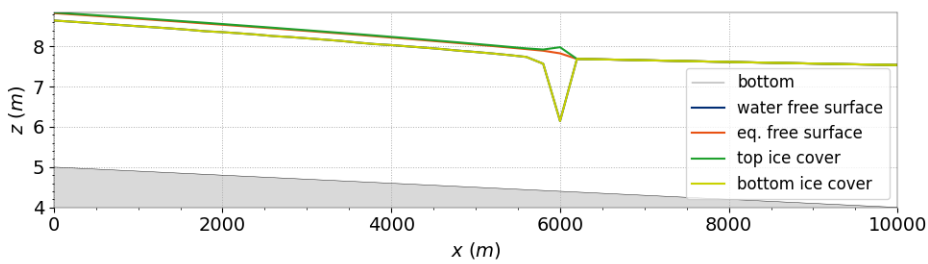



Figure 6.13: Resulting free surface and ice cover

## 6.4 Conclusions

The hydrodynamic of TELEMAC-2 D has been appropriately modified to account for the presence of the ice cover and for the additional shear stress observed at the interface between the ice cover and the water.

# 7. Mass exchange between suspended frazil ice and ice cover

## 7.1 Purpose

The aim of this test case is to test the implementation of the frazil buoyancy velocity and deposition at the free surface. The accumulation of frazil at the surface and the formation of slush ice is modeled and described with its thickness and surface ice fraction.

## 7.2 Description

### 7.2.1 Geometry, mesh and bathymetry

The domain is a long flat-bottom flume, boxed within $(x = 0, y = 0)$ and $(x = 10,000, y = 150)$, its length being $10km$ along the x-axis and its width being $150m$ along the y-axis. The channel has a slope of 1:10,000 between the elevation $5m$ (upstream) and $4m$ (downstream).

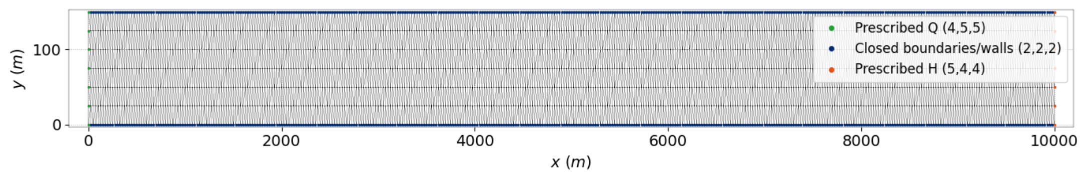



Figure 7.1: Domain mesh.

The mesh of the domain was created with a uniform density of about $0.35m$, resulting in a mesh with 4800 elements and 2807 vertices (cf. figure 7.1).

### 7.2.2 Initial conditions

A hydrodynamics steady state condition is established first separately to reach a constant and uniform water depth of $6.6265m$ and a constant and uniform discharge of $300m^3/s$. Water temperature is initially set at $0.05°C$. Initial frazil volume fraction is set to 0. These values are also used for the upstream boundary condition. Figure 7.2 shows the initial water elevation profile.

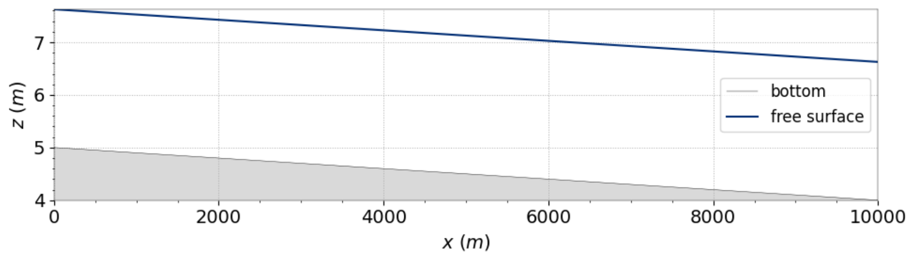



Figure 7.2: Initial elevation profile.

### 7.2.3 Boundary conditions

There are two solid boundaries and 2 open boundaries. The solid boundaries are on either side of the length of the flume, considered as solid walls with perfect slip conditions. The open boundaries are at $(x = 0)$ for the upstream and at $(x = 10,000)$ for the downstream of the flume. A constant discharge of $300m^3/s$ is imposed at the upstream boundary with a temperature set to $0.05°C$. A constant water level is set at $6.6265m$ at the downstream boundary. A first simulation is carried out with for the hydrodynamics only to get to a steady state equilibrium of a constant and uniform water depth of $6.6265m$ and a constant and uniform discharge of $300m^3/s$ along the entire length of the flume.

### 7.2.4 Atmospheric drivers

For this test case, linear heat exchanges are used i.e. within the KHIONE steering file:

- ▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi^* = \phi_R + \alpha + \beta(T_{air} - T_{water}) \tag{7.1}$$

where $\phi_R$ the net solar radiation flux, which depends on the solar constant $I_{so}$ and the latitude but also atmospheric properties like the nebulosity and the visibility. $\alpha$ and $\beta$ are two coefficient that are set to $-50W.m^{-2}$ and $20W.m^{-2}.K^{-1}$ by default. $I_{so}$ is set to zero in the KHIONE steering file: *SOLAR CONSTANT = 0.*. Air temperature is set to $-20°C$.

### 7.2.5 Physical parameters

In order to balance the slope and the discharge through the flume, a Manning friction law is used, with a coefficient of 0.025.
Physical properties related to frazil growth rate are defined in the KHIONE steering file. In this test case, $N_u$, $r$, $R$ are defined with their default values.
Physical properties related to the mass-exchanges between suspended frazil ice and the ice cover are defined as:

- ▷ *MODEL FOR MASS EXCHANGE BETWEEN FRAZIL AND ICE COVER = 1*
- ▷ *FRAZIL UNDER COVER DEPOSITION PROBABILITY = 1.*

Finally, the ice cover parameters are set as:

- ▷ *DYNAMIC ICE COVER = YES*
- ▷ *INITIAL COVER CONCENTRATION VALUE = 0.*

- ▷ *INITIAL COVER THICKNESS VALUE = 0.*
- ▷ *PRESCRIBED COVER CONCENTRATION VALUES = 0.;0.*
- ▷ *PRESCRIBED COVER THICKNESS VALUES = 0.;0.*

### 7.2.6 Numerical parameters

The time step is set to $1s$ and the number of timestep is set to 10800 which leads to a simulation time of $3h$.

## 7.3 Results

The figures 7.3 and 7.4 show the temperature and the frazil concentration along the flume at different times. The surface ice fraction and thickness are also plotted along the flume in figures 7.5 and 7.6.

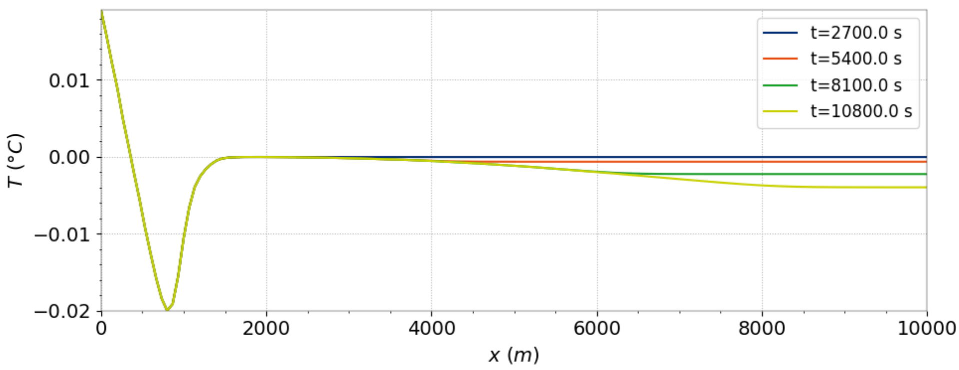



Figure 7.3: Water temperature along the flume.

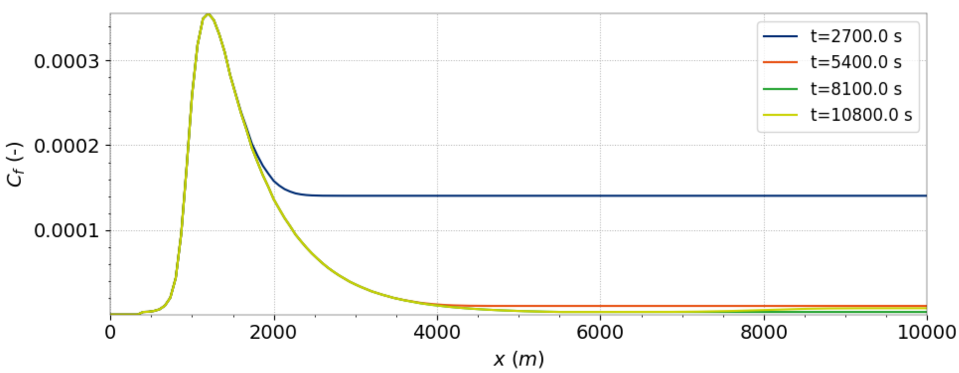



Figure 7.4: Frazil ice concentration along the flume.

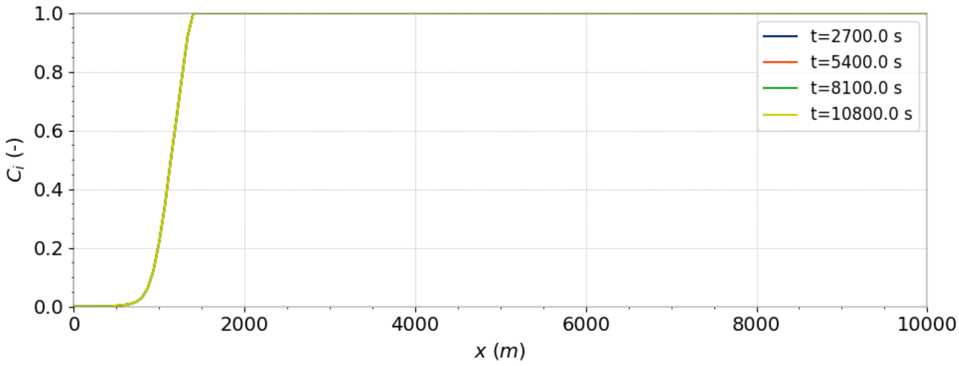



Figure 7.5: Ice cover surface fraction along the flume.

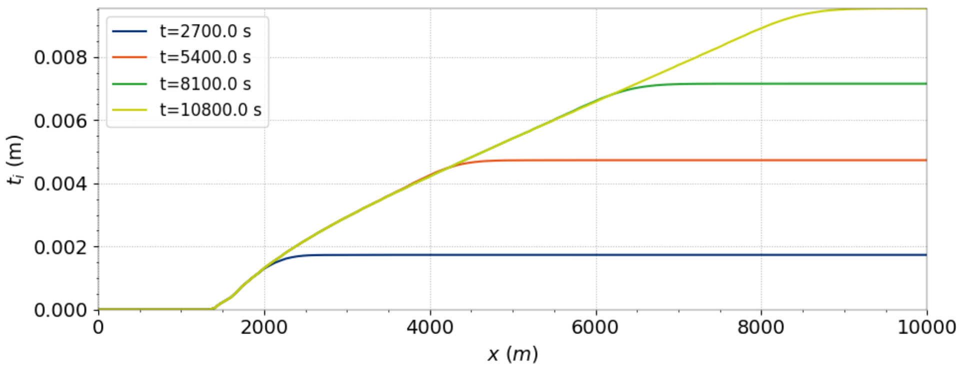



Figure 7.6: Ice cover thickness along the flume.

On figures 7.8 and 7.7 the frazil concentration and temperature are plotted along the flume at final time. Figure 7.9 shows the surface fraction of the ice cover at the final time, and 7.10 shows the thickness of the ice cover.

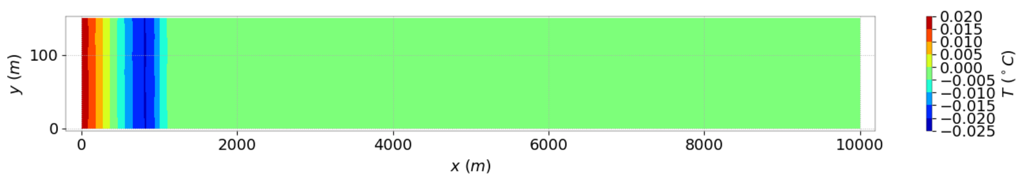



Figure 7.7: Water temperature along the flume at final time.

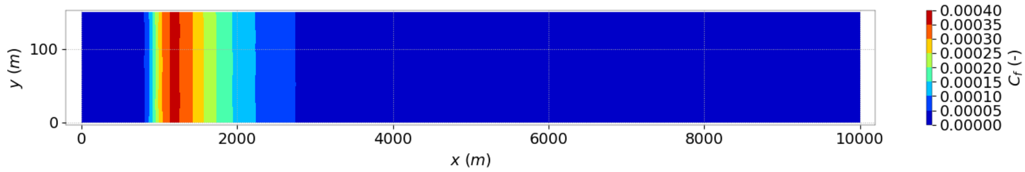



Figure 7.8: Frazil ice concentration along the flume at final time.

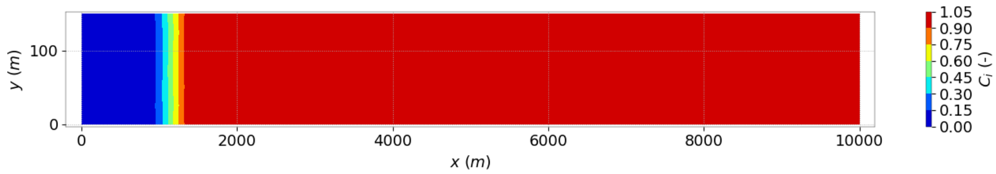



Figure 7.9: Ice cover surface fraction at final time.

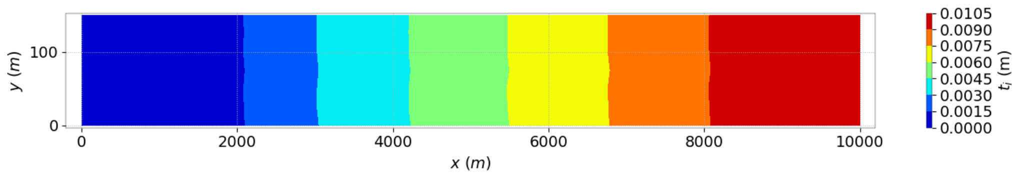



Figure 7.10: Ice cover thickness at the final time.

## 7.4 Conclusions

KHIONE is able to simulate the deposition of suspended frazil ice at the free surface (slush ice formation).

# 8. Validation with Carstens experiments (1966)

## 8.1 Purpose

This test case consists in reproducing the experiments carried out by Carstens in 1966 [1] to demonstrate that KHIONE is capable of correctly fit with supercooling experimental data. Two experiments with two different cooling rates are reproduced with KHIONE with both the MSC[1] and SSC[2] suspended frazil ice models.

## 8.2 Description

### 8.2.1 Geometry, mesh and bathymetry

Carstens experiments [3] were conducted in a recirculating oval flume of about 6 m long, 30 cm deep and 20 cm wide. Water depth was set to 20cm and temperature was recorded at approximately 5 to 10 cm deep with a mercury thermometer marked to 0.01 $^\circ C$.

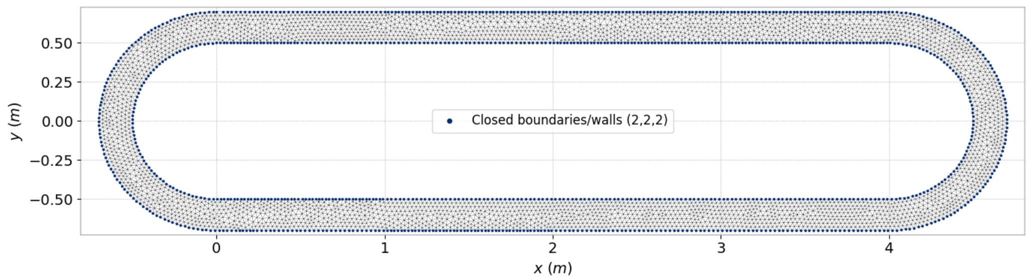



Figure 8.1: Domain mesh

### 8.2.2 Initial conditions

A momentum source term is introduced to simulate the propeller. The source term is adjusted in order to reach an hydrodynamic steady state with a mean flow velocity of 0.5 m.s$^{-1}$. Water temperature is initially set at $0^\circ C$ as well as the initial frazil volume fraction is set to 0.

[1]MSC : multiple-size-class
[2]SSC : single-size-class

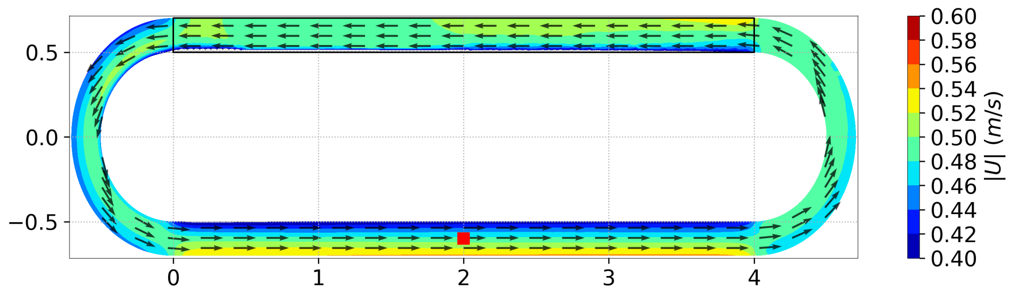



Figure 8.2: Computed hydrodynamic steady state during the experiments. The black box represent the location of the propeller momentum source term and the red dot is where the extraction of frazil ice volume fraction and temperature are done.

### 8.2.3 Boundary conditions

The solid boundaries are on each side of the racetrack, considered as solid walls with perfect slip conditions.

### 8.2.4 Atmospheric drivers

For this test case, linear heat exchanges are used i.e. within the KHIONE steering file:

▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi^* = \phi_R + \alpha + \beta (T_{air} - T_{water}) \tag{8.1}$$

where $\phi_R$ the net solar radiation flux, $\alpha$ and $\beta$ are two coefficient. To match the exact constant cooling rate as in the experiments (cf. table 9.1), $I_{so}$ and $\beta$ are set to zero within the KHIONE steering file. Only $\alpha$ is set depending on the coling rate of the experiment (1 or 2) and the water depth i.e. *WATER-AIR HEAT EXCHANGE CONSTANT = -280* for the first experiment and *WATER-AIR HEAT EXCHANGE CONSTANT = -110* for the second experiment.

### 8.2.5 Physical parameters

The physical parameters of the experiment are summed up in the Table 9.1.

| Case | $H\ (m)$ | $U\ (m/s)$ | Cooling rate $(W/m^3)$ | $S\ (ppt)$ | $k\ (m^2/s^2)$ | $\varepsilon\ (m^2/s^3)$ |
|---|---|---|---|---|---|---|
| Carstens I | 0.2 | 0.5 | 1400 | 0 | $9.6 \cdot 10^{-4}$ | $1.2 \cdot 10^{-3}$ |
| Carstens II | 0.2 | 0.5 | 550 | 0 | $4.8 \cdot 10^{-4}$ | $3.8 \cdot 10^{-4}$ |

Table 8.1: Physical parameters of the experiments.

Physical properties related to frazil growth rate are defined in the KHIONE steering file. For both the SSC and MSC models, the turbulent parameters are set to constants and defined with the keywords:

▷ *MODEL FOR ESTIMATION OF TURBULENCE PARAMETERS = 0*

▷ *CONSTANT TURBULENCE PARAMETERS = KT, EPS, ALPHA*

where *KT, EPS, ALPHA* depends on the experiment and stand for turbulent kinetic energy ($k$), turbulent dissipation rate ($\varepsilon$) and turbulent instensity ($\alpha_t$) respectively. The Nusselt number is then computed within KHIONE depending on these parameters, with *MODEL FOR THE NUSSELT NUMBER = 2*.

#### SSC model parameters

With the SSC model, frazil ice related parameters are set to the following for both experiments:

- ▷ *NUMBER OF CLASSES FOR SUSPENDED FRAZIL ICE = 1*
- ▷ *FRAZIL CRYSTALS RADIUS = 4.1E-4*
- ▷ *FRAZIL CRYSTALS DIAMETER THICKNESS RATIO = 10.*

The initial seeding is defined with a minimum threshold for the number of crystals per unit volume.

- ▷ *MODEL FOR FRAZIL SEEDING = 1*
- ▷ *MINIMUM NUMBER OF FRAZIL CRYSTALS = 7.1586E4*

The parameter *MINIMUM NUMBER OF FRAZIL CRYSTALS* is set to default values.

#### MSC model parameters

With the MSC model, frazil ice crystal' sizes are defined as:

- ▷ *NUMBER OF CLASSES FOR SUSPENDED FRAZIL ICE = 10*
- ▷ *FRAZIL CRYSTALS RADIUS = 1.E-4 ; 1.2915E-4 ; 1.6681E-4 ; 2.1544E-4 ; 2.7826E-4; 3.5938E-4 ; 4.6416E-4 ; 5.9948E-4 ; 7.7426E-4 ; 1.E-3*
- ▷ *FRAZIL CRYSTALS DIAMETER THICKNESS RATIO = 10.*

Similarly to the SSC system, the initial seeding is defined with a minimum threshold for the number of crystals. The parameter *MINIMUM NUMBER OF FRAZIL CRYSTALS* is defined in the table 9.2.

| Case | $\alpha_{floc}$ $(s^{-1})$ | $n_{max}$ | $N_0$ $(m^{-3})$ |
|---|---|---|---|
| Carstens I | $10^{-4}$ | $8. \times 10^6$ | $5.88717 \times 10^5$ |
| Carstens II | $10^{-4}$ | $4. \times 10^6$ | $4.86332 \times 10^5$ |

Table 8.2: Calibrated parameters.

Two new processes are taken into account compared to the SSC, which are the secondary nucleation and the flocculation processes for which the parameters are defined as follows:

- ▷ *MODEL FOR THE BUOYANCY VELOCITY = 2*
- ▷ *MODEL FOR THE SECONDARY NUCLEATION = 2*
- ▷ *SECONDARY NUCLEATION NMAX PARAMETER = see table 9.2*
- ▷ *MODEL FOR THE FLOCCULATION AND BREAKUP = 1*
- ▷ *FLOCCULATION AFLOC PARAMETER = see table 9.2*

The parameters $n_{max}$ and $a_{floc}$ parameters are taken as calibration parameters that are tuned to fit with the experimental data.

### 8.2.6 Numerical parameters

The time step is set to 0.05s and the simulation time is set to 600s.

## 8.3 Results

Total frazil volume fraction and temperature are plotted against time $t^* = t/t_c$ where the characteristic time $t_c$ corresponds to the moment when 90 percent of the maximum temperature depression is recovered. Frazil volume fraction is computed as $C^* = C/C(t_c)$.

### SSC model:

The figure 8.3 show the temperature and the frazil volume fraction results with the SSC model against Carstens I and II experimental data.

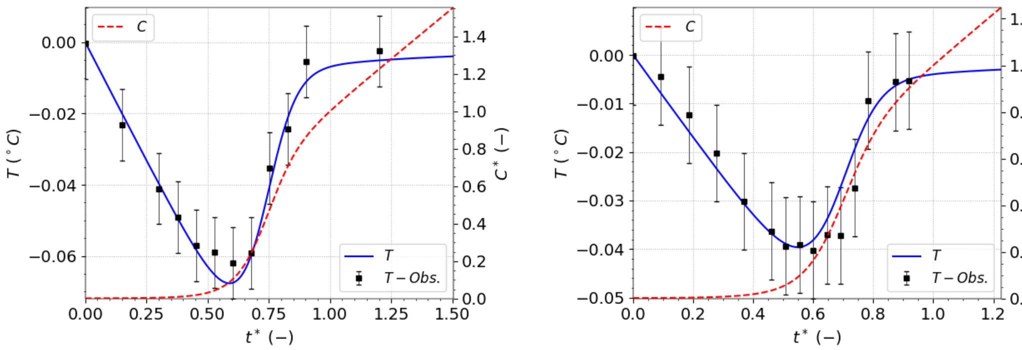



Figure 8.3: Simulated temperature and total frazil volume fraction with comparison to Carstens experiments I (left) and II (right).

### MSC model:

The figure 8.4 show the temperature and the total frazil volume fraction results with the MSC model against Carstens I and II experimental data.

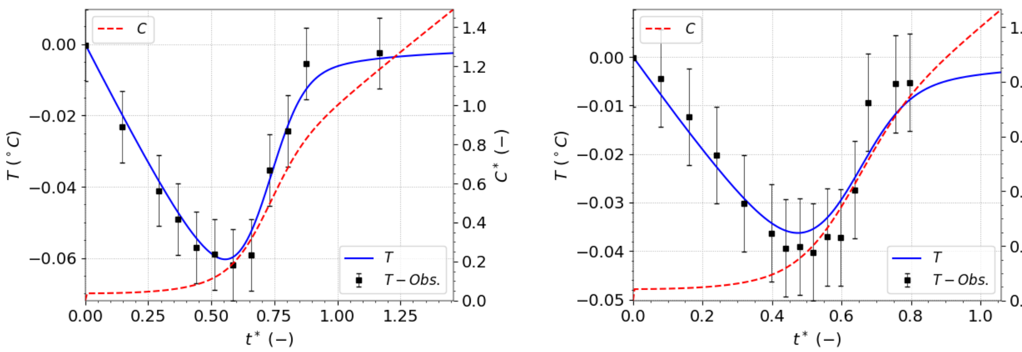



Figure 8.4: Simulated temperature and total frazil volume fraction with comparison to Carstens experiments I (left) and II (right).

## 8.4 Conclusions

Both sinlge- and multiple-size-class frazil ice models are able to reproduce the supercooling sequence with adequate calibration of input parameters.

# 9. Validation with Tsang & Hanley experiments (1984)

## 9.1 Purpose

This test case consists in reproducing the experiments carried out by Tsang & Hanley in 1984 [2] to demonstrate that KHIONE is capable of correctly fit with supercooling and frazil ice growth experimental data. Experiments are carried out with saline water and several initial seeding times are tested. These experiments are reproduced with KHIONE with both the MSC[1] and SSC[2] suspended frazil ice models.

## 9.2 Description

### 9.2.1 Geometry, mesh and bathymetry

Tsang & Hanley experiments [2] (C) were conducted in a recirculating, racetrack shaped, flume of 65 cm long, 13 cm deep and 15 cm wide. The tank was filled with sea-water of salinity comprised between 29 and 31 ppt. The frazil concentration was estimated using temperature measurements, made with a thermometer calibrated to 0.0001 °C, with repeatability of 0.001 °C. This leads to an absolute error of $1.25 \cdot 10^{-5}$ $m^3 \cdot m^{-3}$ on frazil observations.

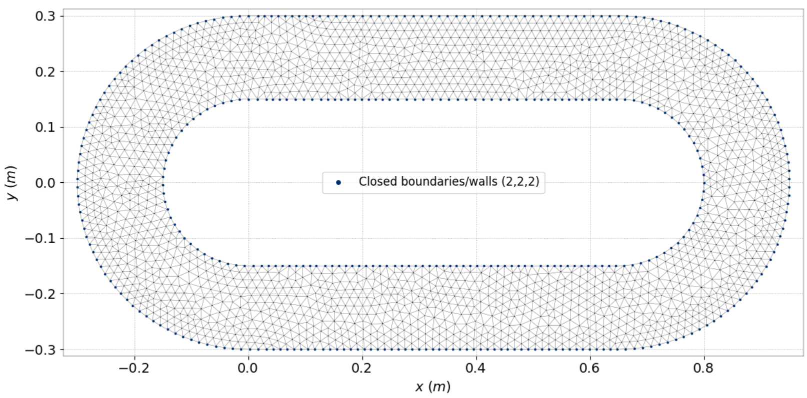



Figure 9.1: Domain mesh

[1]MSC : multiple-size-class
[2]SSC : single-size-class

### 9.2.2 Initial conditions

To reproduce experiments, a momentum source term is introduced to simulate the propeller. The source term is adjusted in order to reach an hydrodynamic steady state with a mean flow velocity of 0.15 m.s$^{-1}$.

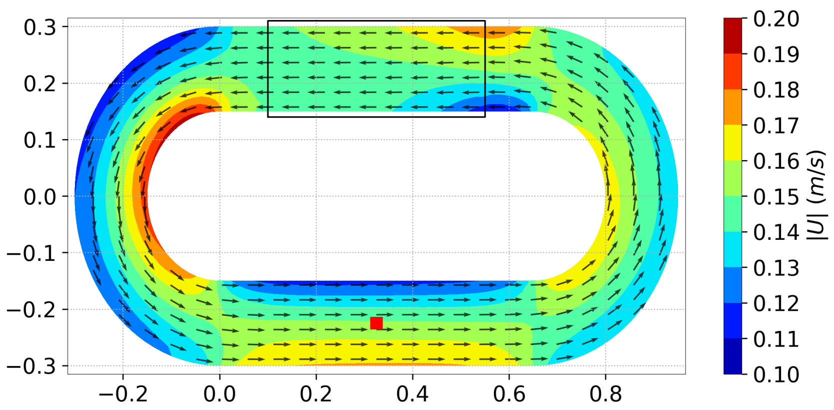



Figure 9.2: Computed hydrodynamic steady state during the experiments. The black box represent the location of the propeller momentum source term and the red dot is where the extraction of frazil ice volume fraction and temperature are done.

### 9.2.3 Boundary conditions

The solid boundaries are on each side of the racetrack, considered as solid walls with perfect slip conditions.

### 9.2.4 Atmospheric drivers

For this test case, linear heat exchanges are used i.e. within the KHIONE steering file:

▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 0*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi^* = \phi_R + \alpha + \beta(T_{air} - T_{water}) \tag{9.1}$$

where $\phi_R$ the net solar radiation flux, $\alpha$ and $\beta$ are two coefficient. To match the exact constant cooling rate as in the experiments (cf. table 9.1), $I_{so}$ and $\beta$ are set to zero within the KHIONE steering file. Only $\alpha$ is set to match the coling rate of the experiment: *WATER-AIR HEAT EXCHANGE CONSTANT = -13.42*.

### 9.2.5 Physical parameters

The physical parameters of the experiment are summed up in the Table 9.1.

| Case | $H$ $(m)$ | $U$ $(m/s)$ | Cooling rate $(W/m^3)$ | $S$ $(ppt)$ | $k$ $(m^2/s^2)$ | $\varepsilon$ $(m^2/s^3)$ |
|---|---|---|---|---|---|---|
| (C) | 0.11 | 0.15 | 122 | $29-31$ | $7 \cdot 10^{-6}$ | $2.36 \cdot 10^{-6}$ |

Table 9.1: Physical parameters of the experiments.

Physical properties related to frazil growth rate are defined in the KHIONE steering file. For both the SSC and MSC models, the turbulent parameters are set to constants and defined with the keywords:

- *MODEL FOR ESTIMATION OF TURBULENCE PARAMETERS = 0*
- *CONSTANT TURBULENCE PARAMETERS = 7.E-6; 2.36E-6; 3.18E-2*

with respectively the turbulent kinetic energy ($k$), the turbulent dissipation rate ($\varepsilon$) and turbulent instensity ($\alpha_t$). The Nusselt number is then computed within KHIONE depending on these parameters, with *MODEL FOR THE NUSSELT NUMBER = 2*.

#### SSC model parameters

With the SSC model, frazil ice related parameters are set to default for both experiments:

- *NUMBER OF CLASSES FOR SUSPENDED FRAZIL ICE = 1*
- *FRAZIL CRYSTALS RADIUS = 4.1E-4*
- *FRAZIL CRYSTALS DIAMETER THICKNESS RATIO = 10.*

The initial seeding is defined with a minimum threshold for the number of crystals per unit volume.

- *MODEL FOR FRAZIL SEEDING = 1*
- *MINIMUM NUMBER OF FRAZIL CRYSTALS = 7.1586E4*

The parameters *MINIMUM NUMBER OF FRAZIL CRYSTALS* is set to its default value.

#### MSC model parameters

With the SSC model, frazil ice crystal' sizes are defined as:

- *NUMBER OF CLASSES FOR SUSPENDED FRAZIL ICE = 10*
- *FRAZIL CRYSTALS RADIUS = 1.E-4 ; 1.2915E-4 ; 1.6681E-4 ; 2.1544E-4 ; 2.7826E-4; 3.5938E-4 ; 4.6416E-4 ; 5.9948E-4 ; 7.7426E-4 ; 1.E-3*
- *FRAZIL CRYSTALS DIAMETER THICKNESS RATIO = 10.*

Similarly to the monoclass system, the initial seeding is defined with a minimum threshold for the number of crystals per unit volume. The parameters *MINIMUM NUMBER OF FRAZIL CRYSTALS* is defined in the table 9.2.

| Case | $\alpha_{floc}$ ($s^{-1}$) | $n_{max}$ | $N_0$ ($m^{-3}$) |
|---|---|---|---|
| (C) | $10^{-4}$ | $6. \times 10^6$ | $5.88717 \times 10^5$ |

Table 9.2: Calibrated parameters.

Two new processes are taken into account compared to the SSC, which are the secondary nucleation and the flocculation processes for which the parameters are defined as follows:

- *MODEL FOR THE BUOYANCY VELOCITY = 2*
- *MODEL FOR THE SECONDARY NUCLEATION = 2*
- *SECONDARY NUCLEATION NMAX PARAMETER = see table 9.2*
- *MODEL FOR THE FLOCCULATION AND BREAKUP = 1*
- *FLOCCULATION AFLOC PARAMETER = see table 9.2*

The parameters $n_{max}$ and $a_{floc}$ parameters are taken as calibration parameters that are tuned to fit with the experimental data.

### 9.2.6 Numerical parameters

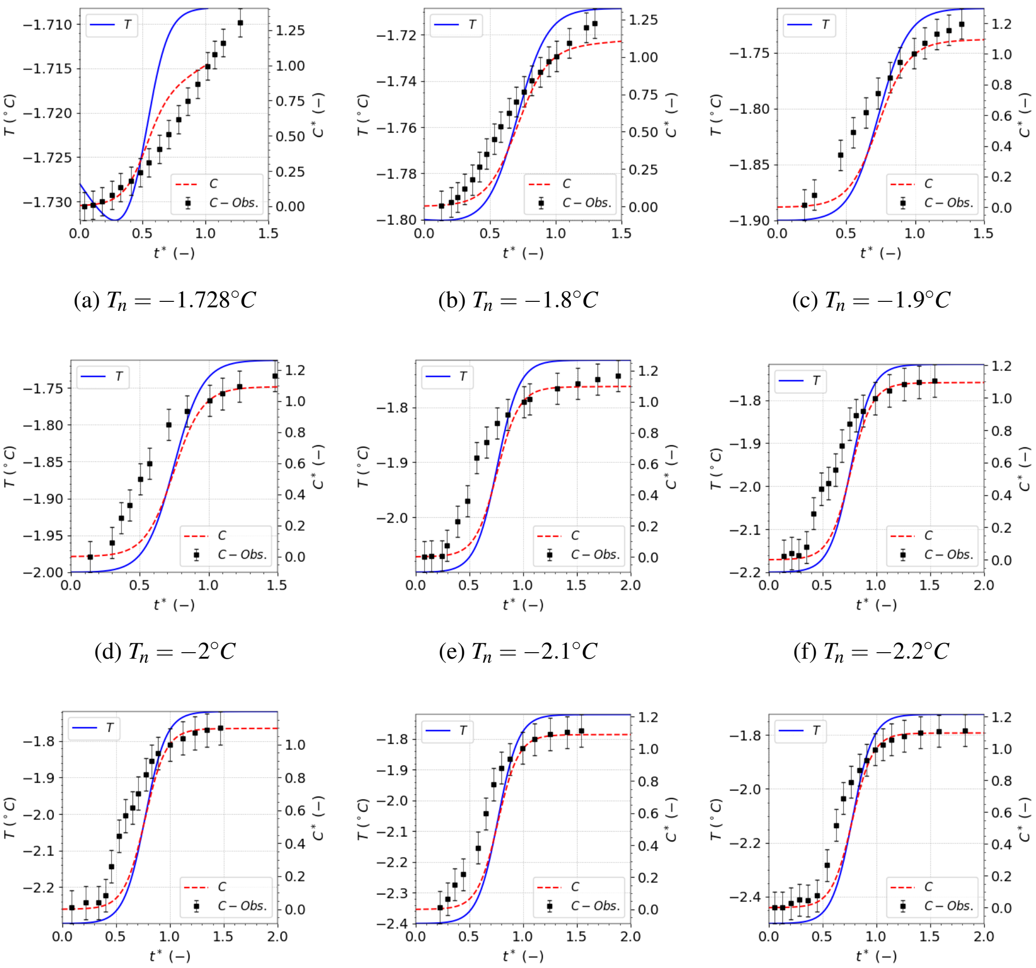
The time step is set to 0.01s and the simulation time is set to 600s.

## 9.3 Results

Total frazil volume fraction and temperature are plotted against time $t^* = t/t_c$ where the characteristic time $t_c$ corresponds to the moment when 90 percent of the maximum temperature depression is recovered.

#### SSC model:

The figure 9.3 show the temperature and the frazil volume fraction results with the SSC model against Tsang & Hanley experimental data at different seeding temperature.




(a) $T_n = -1.728°C$ (b) $T_n = -1.8°C$ (c) $T_n = -1.9°C$

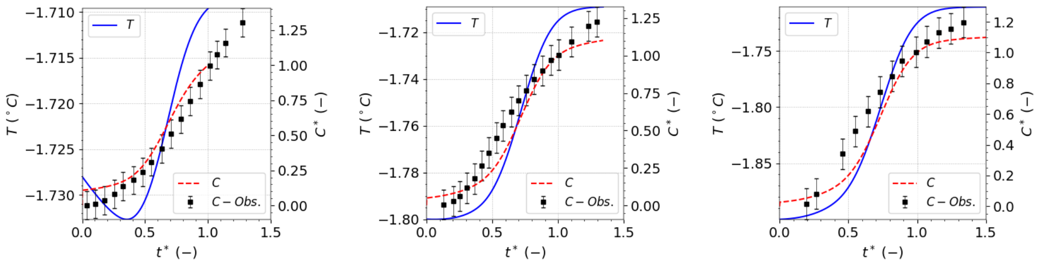
(d) $T_n = -2°C$ (e) $T_n = -2.1°C$ (f) $T_n = -2.2°C$

(g) $T_n = -2.3°C$ (h) $T_n = -2.4°C$ (i) $T_n = -2.5°C$

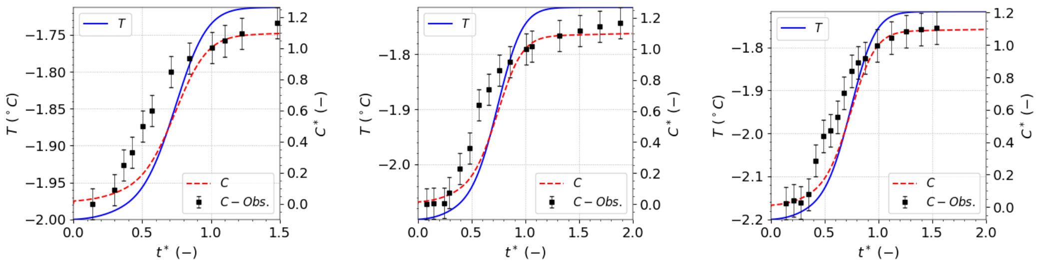
Figure 9.3: Simulated temperature and normalized total frazil volume fraction with comparison to Tsang & Hanley experiments for different seeding temperature with the SSC model.

#### MSC model:

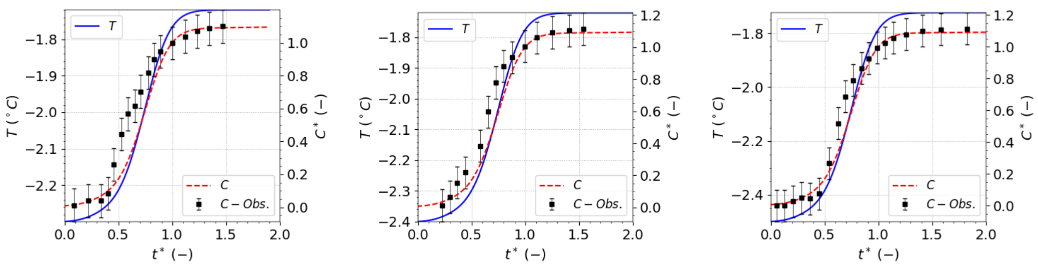
The figure 9.4 show the temperature and the total frazil volume fraction results with the MSC model against Tsang & Hanley experimental data at different seeding temperature.




(a) $T_n = -1.728°C$ (b) $T_n = -1.8°C$ (c) $T_n = -1.9°C$




(d) $T_n = -2°C$ (e) $T_n = -2.1°C$ (f) $T_n = -2.2°C$




(g) $T_n = -2.3°C$ (h) $T_n = -2.4°C$ (i) $T_n = -2.5°C$

Figure 9.4: Simulated temperature and normalized total frazil volume fraction with comparison to Tsang & Hanley experiments for different seeding temperature with the MSC model.

## 9.4 Conclusions

The confrontation of numerical results to experimental data is encouraging as both models are able to reproduce supercooling and temperature recovery under different turbulent and salinity conditions.

# 10. Saint Lawrence

## 10.1 Purpose

The border ice formation in the reach of St. Lawrence River from Ogdensburg to Power Dam is simulated to test the applicability of the border ice module. This reach is an ideal channel to examine the border ice module because of the complex geometry with number of islands and large variation of flow depth. This test case also demonstrates that KHIONE is capable of modeling frazil ice formation, transport accumulation at the free surface in a real life configuration.

## 10.2 Description

### 10.2.1 Geometry, mesh and bathymetry

The domain upstream boundary is set to Ogdensburg and the downstream is set to the Power Dam.

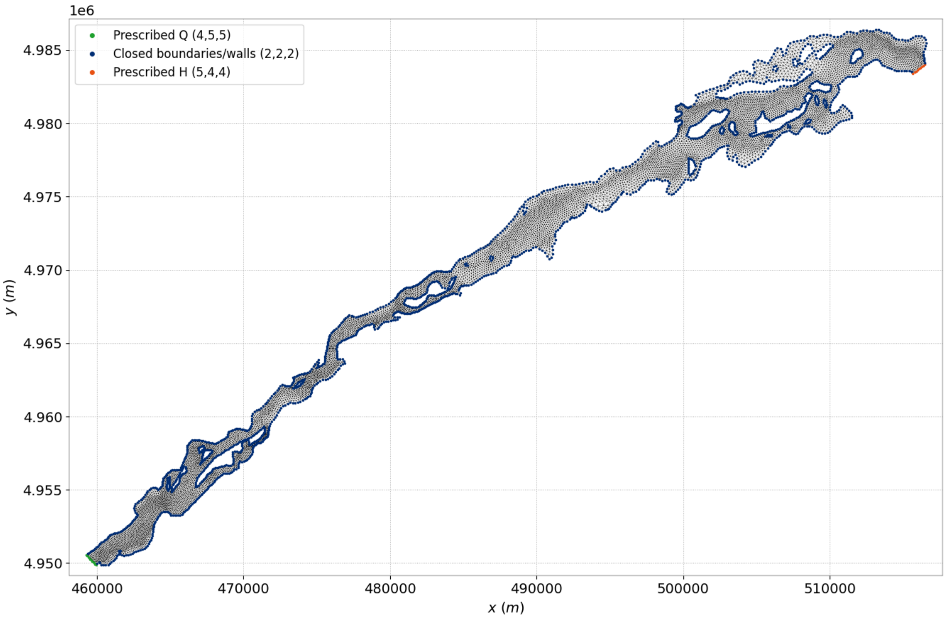



Figure 10.1: Domain mesh

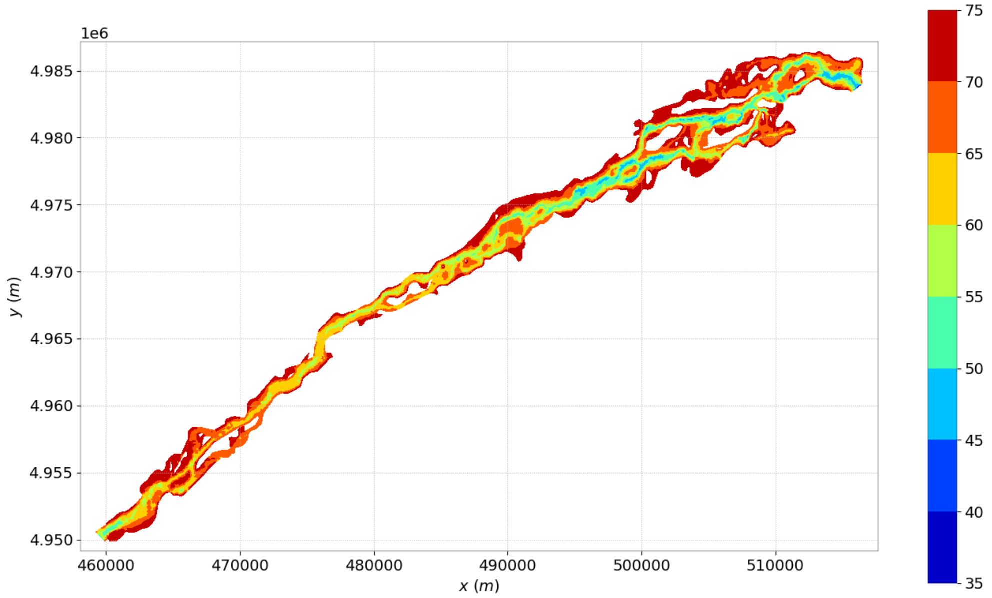



Figure 10.2: Bathymetry

### 10.2.2 Initial conditions

A hydrodynamics steady state condition is established first separately to reach a constant and uniform elevation and a constant and uniform discharge. Water temperature is initially set at $0.0°C$.

### 10.2.3 Atmospheric drivers and boundary conditions

In Figure 10.3 the observed discharge and air temperature are given for the winter of 2019. Several freeze-up periods are highlighted.

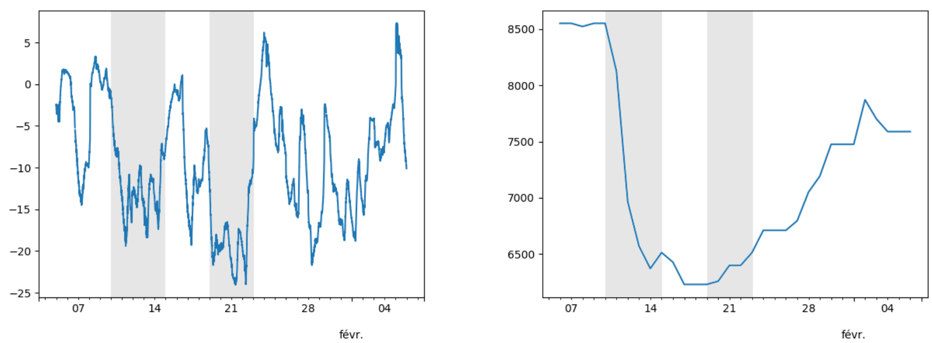



Figure 10.3: Measured air temperature at Station OBGN6 (8311030 Ogdensburg) and measured discharge during winter 2019 at Robert Moses-Robert H. Saunders power dam on Lake St. Lawrence (source: USGS)

There are 2 open boundaries as described in Figure 10.1. The solid boundaries are considered as solid walls with perfect slip conditions. A constant water surface elevation of 74.40 m is considered at the upstream boundary and a constant discharge of 6400m$^3$/s is imposed at the

downstream boundary.
For this test case, the full heat exchanges are used i.e. within the KHIONE steering file:

- ▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 1*

Air temperature is set to a constant of $-20°$ during the simulation.

### 10.2.4 Physical parameters

In order to balance the slope and the discharge through the flume, a Manning friction law is used, with a coefficient of 0.025.
To activate the simulation of border ice processes, the following keywords are added to the KHIONE steering file:

- ▷ *BORDER ICE COVER = YES*
- ▷ *ICE COVER IMPACT ON HYDRODYNAMIC = YES*

### 10.2.5 Numerical parameters

The time step is set to $1s$ and the number of timestep is set to 86400 which leads to a simulation time of one day.

## 10.3 Results

Figure 10.5 shows the simulated steady state water velocity. Figure 10.6 and Figure 10.7 show the good agreement between observed and simulated border ice distribution in the St. Lawrence River.

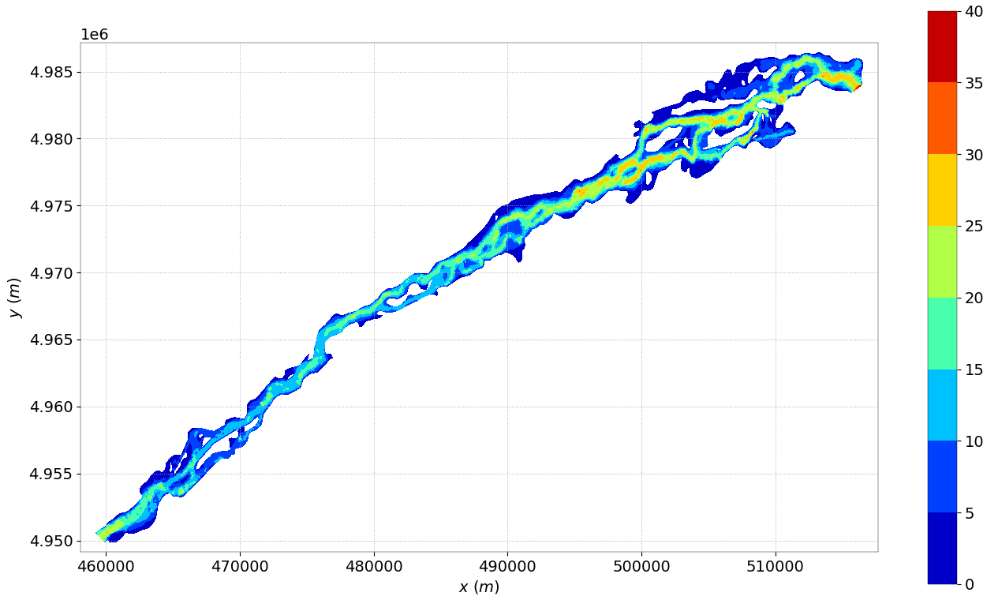



Figure 10.4: Simulated steady state water depth.

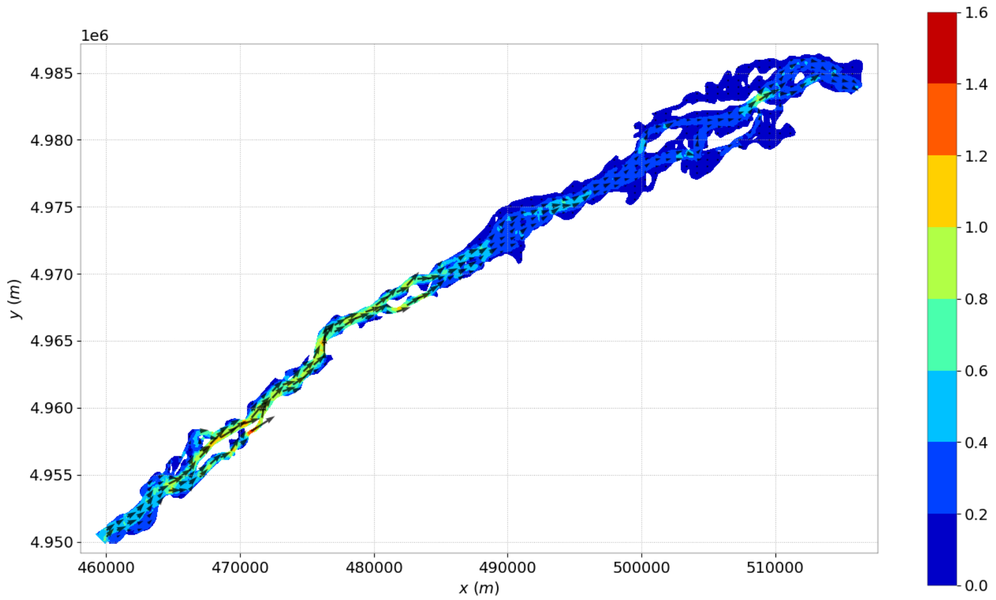



Figure 10.5: Simulated steady state water velocity.

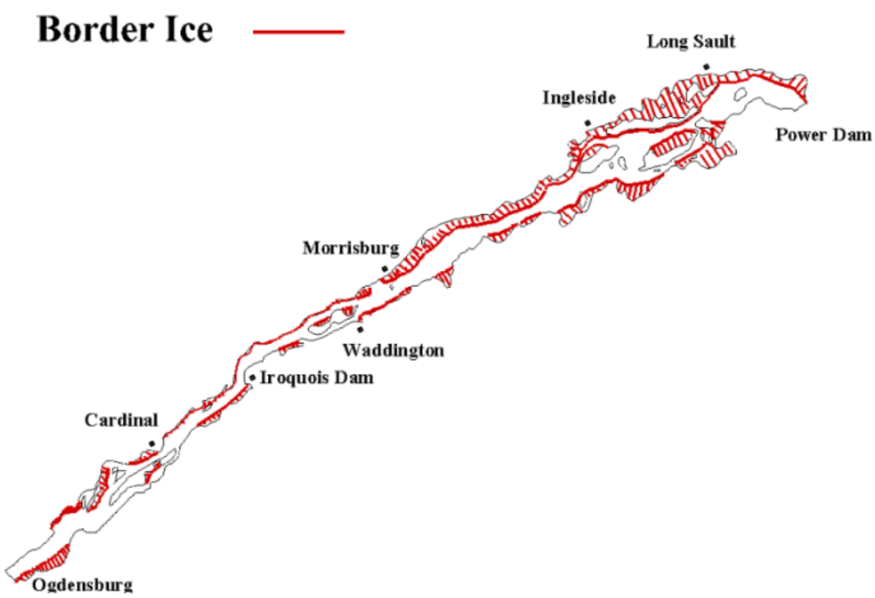



Figure 10.6: Observed typical border ice distribution during freeze up in the St. Lawrence River.

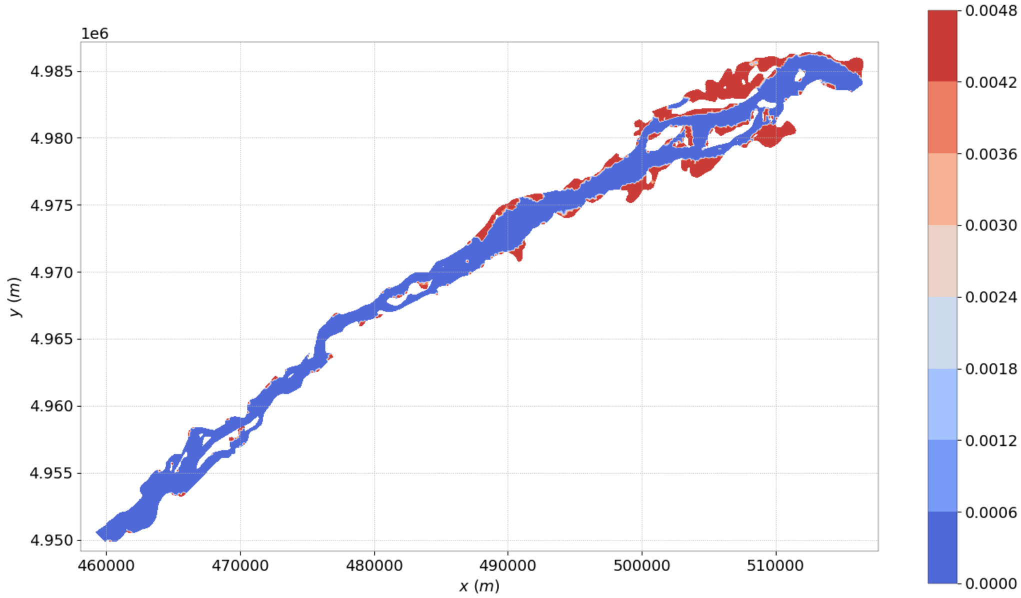



Figure 10.7: Simulated border ice thickness in the St. Lawrence River.

## 10.4 Conclusions

This test case shows the ability of KHIONE to model the formation of border ice along a river during a freeze-up period.

# 11. Thermal budget

## 11.1 Purpose

This test case demonstrates that KHIONE is able of correctly model heat exchanges at the free surface depending on atmsopheric data. In this test case, atmospheric input data is taken from Massena, NY, USA, near the St Laurence River. The results are compared to CRISSP2D code.

## 11.2 Model description

### 11.2.1 Geometry and mesh

The domain is a square box, centred on $(0;0)$, with a size of $4m$ x $4m$. The box has a flat bottom, set at $0m$. The mesh of the domain was created with a uniform density of about $0.35m$, resulting in a mesh with 332 elements and 193 vertices. (see figure 12.1).

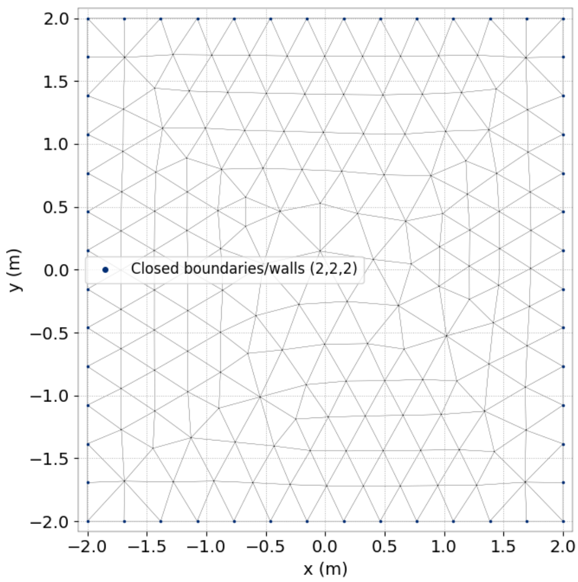



Figure 11.1: Domain mesh

### 11.2.2 Initial conditions

Water is at rest and remains so during the simulation. Water depth is set to 1 m. Water temperature is initially set at $1°C$.

### 11.2.3 Boundary conditions

Boundaries are considered as solid walls with perfect slip conditions.

### 11.2.4 Atmospheric drivers

There are no other drivers than the atmospheric exchanges. Temporal variations in air temperature, cloud cover, dew temperature, visibility, snow, rain and wind speed are provided through the ASCII file within the TELEMAC-2 D steering file. Also, in order to refer to the angle of the sun, the latitude of the model is provided in the TELEMAC-2 d seering file:

▷ *LATITUDE OF ORIGIN POINT = 44.73*

▷ *ASCII ATMOSPHERIC DATA FILE* = 't2d_meteo.lqd'

For constant atmospheric data over time, values can also be set within the KHIONE steering file:

▷ *AIR TEMPERATURE = -10.0*

▷ *DEWPOINT TEMPERATURE = 0.0*

▷ *CLOUD COVER = 0.0*

▷ *VISIBILITY = 1.E9*

▷ *RAIN = 0.0*

▷ *WIND XY-COMPONENTS = 5.;3.*

▷ *RELATIVE MODEL ELEVATION FROM MEAN SEA LEVEL = 80.*

For the full thermal budget the heat exchange model is set to 4 within KHIONE streering file:

▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 2*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi = \phi_R + C_B\phi_B + C_E\phi_E + C_H\phi_H + C_P\phi_P \tag{11.1}$$

where $\phi_R$, $\phi_B$, $\phi_E$, $\phi_H$ and $\phi_P$ are the net solar radiation flux, the effective back radiation flux, the evaporation heat transfert, the conductive heat transfert and the precipitation heat transfert respectively. $C_B$, $C_E$, $C_H$ and $C_P$ are calibration coefficient, with default values of 1., that are defined in the KHIONE steering file via the folling keywords:

▷ *COEFFICIENT FOR CALIBRATION OF BACK RADIATION = 1.*

▷ *COEFFICIENT FOR CALIBRATION OF EVAPORATIVE HEAT TRANSFERT = 1.*

▷ *COEFFICIENT FOR CALIBRATION OF CONDUCTIVE HEAT TRANSFERT = 1.*

▷ *COEFFICIENT FOR CALIBRATION OF PRECIPITATION HEAT TRANSFERT = 1.*

### 11.2.5 Physical parameters

Within the WAQTEL steering file, water and air specific heat are set to $1002 J.kg^{-1}.K^{-1}$ and $4180 J.kg^{-1}.K^{-1}$.

### 11.2.6 Numerical parameters

The time step is set to $300s$ and the number of timestep is set to 288 which leads to a simulation time of $24h$.

### 11.2.7 Reference data

KHIONE results are compared against results obtained from the modelling framework CRISSP2D originally developed by Clarkson University, NY, USA.

## 11.3 Results

On figure 12.2 and 12.4 thermal fluxes and water temperature evolution are plotted against time with the comprehensive thermal budget model. For comparison, the thermal fluxes at the free surface obtained with the simplified linear model are plotted in Figure 12.3.

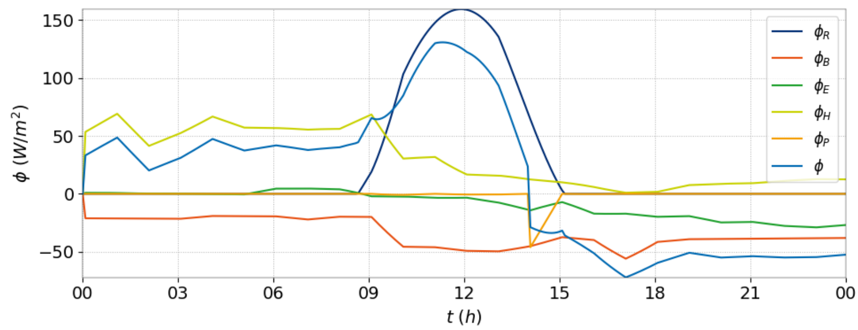



Figure 11.2: Thermal fluxes at the free surface with the full budget model

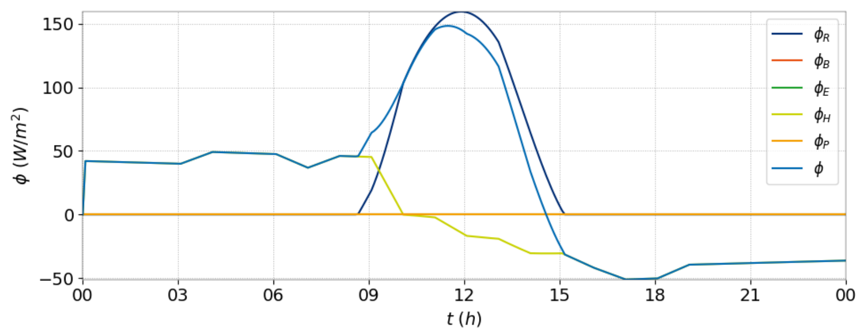



Figure 11.3: Thermal fluxes at the free surface with the default linear budget model

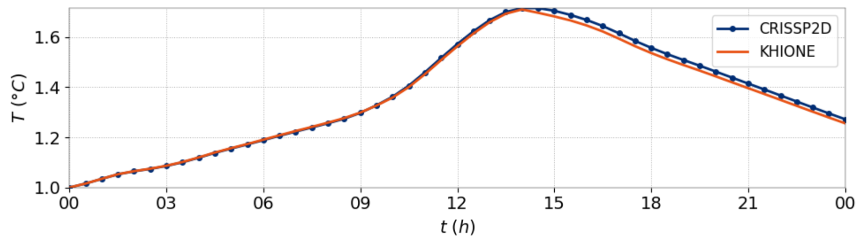



Figure 11.4: Evolution of the water temperature

## 11.4 Conclusions

The water remains at rest and the tracer (temperature) evolve as a result of changes in the atmospheric conditions (air temperature, solar radiation, etc.). The variation in temperature over the 24 hour period is exactly as computed originally by Clarkson University in CRISSP2D.

# 12. Thermal budget - 3D

## 12.1 Purpose

This test case demonstrates that KHIONE is able of correctly model heat exchanges at the free surface depending on atmsopheric data. In this test case, atmospheric input data is taken from Massena, NY, USA, near the St Laurence River.

## 12.2 Model description

### 12.2.1 Geometry and mesh

The domain is a square box, centred on $(0;0)$, with a size of 4 m x 4 m. The box has a flat bottom, set at 0 m. The mesh of the domain was created with a uniform density of about 0.35 m, resulting in a mesh with 332 elements and 193 vertices. (see figure 12.1). The considered mesh is extruded with 2 planes in the vertical dimension.

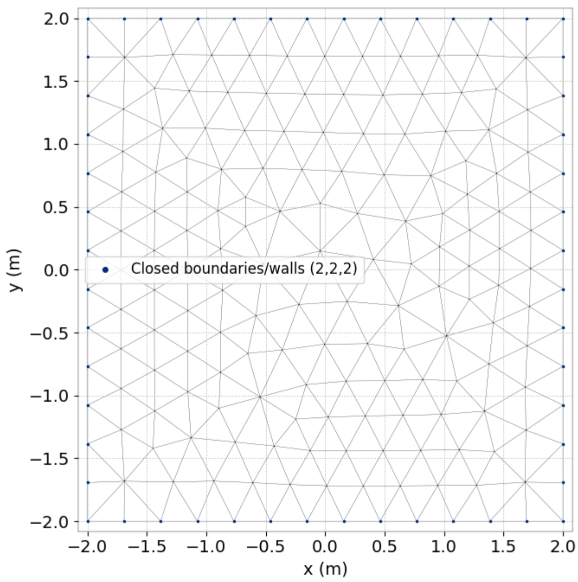



Figure 12.1: Domain mesh

### 12.2.2 Initial conditions

Water is at rest and remains so during the simulation. Water depth is set to 1 m. Water temperature is initially set at 1°C.

### 12.2.3 Boundary conditions

Boundaries are considered as solid walls with perfect slip conditions.

### 12.2.4 Atmospheric drivers

There are no other drivers than the atmospheric exchanges. Temporal variations in air temperature, cloud cover, dew temperature, visibility, snow, rain and wind speed are provided through the ASCII file within the TELEMAC-3D steering file. Also, in order to refer to the angle of the sun, the latitude of the model is provided in the TELEMAC-3D seering file:

▷ *LATITUDE OF ORIGIN POINT = 44.73*

▷ *ASCII ATMOSPHERIC DATA FILE* = 't3d_meteo_stlaurent.lqd'

For constant atmospheric data over time, values can also be set within the KHIONE steering file:

▷ *AIR TEMPERATURE = -10.0*

▷ *DEWPOINT TEMPERATURE = 0.0*

▷ *CLOUD COVER = 0.0*

▷ *VISIBILITY = 1.E9*

▷ *RAIN = 0.0*

▷ *WIND XY-COMPONENTS = 5.;3.*

▷ *RELATIVE MODEL ELEVATION FROM MEAN SEA LEVEL = 80.*

For the full thermal budget the heat exchange model is set to 4 within KHIONE streering file:

▷ *ATMOSPHERE-WATER EXCHANGE MODEL = 2*

With this model, the net heat flux received by water trought the water/air interface is expressed as:

$$\phi = \phi_R + C_B\phi_B + C_E\phi_E + C_H\phi_H + C_P\phi_P \tag{12.1}$$

where $\phi_R$, $\phi_B$, $\phi_E$, $\phi_H$ and $\phi_P$ are the net solar radiation flux, the effective back radiation flux, the evaporation heat transfert, the conductive heat transfert and the precipitation heat transfert respectively. $C_B$, $C_E$, $C_H$ and $C_P$ are calibration coefficient, with default values of 1., that are defined in the KHIONE steering file via the folling keywords:

▷ *COEFFICIENT FOR CALIBRATION OF BACK RADIATION = 1.*

▷ *COEFFICIENT FOR CALIBRATION OF EVAPORATIVE HEAT TRANSFERT = 1.*

▷ *COEFFICIENT FOR CALIBRATION OF CONDUCTIVE HEAT TRANSFERT = 1.*

▷ *COEFFICIENT FOR CALIBRATION OF PRECIPITATION HEAT TRANSFERT = 1.*

### 12.2.5 Physical parameters

Within the KHIONE steering file, water and air specific heat are set to 1002 $J.kg^{-1}.K^{-1}$ and 4180 $J.kg^{-1}.K^{-1}$.

### 12.2.6 Numerical parameters

The time step is set to 300 s and the number of timestep is set to 288 which leads to a simulation time of 24 h.

## 12.3 Results

On Figure 12.2 and 12.4 thermal fluxes and water temperature evolution are plotted against time with the comprehensive thermal budget model. For comparison, the thermal fluxes at the free surface obtained with the simplified linear model are plotted on Figure 12.3.

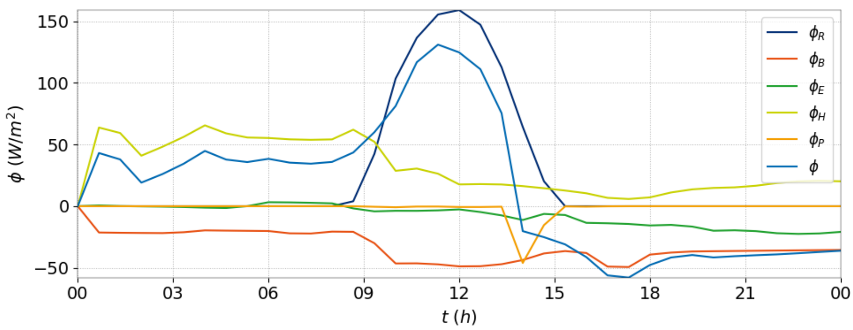



Figure 12.2: Thermal fluxes at the free surface with the full budget model

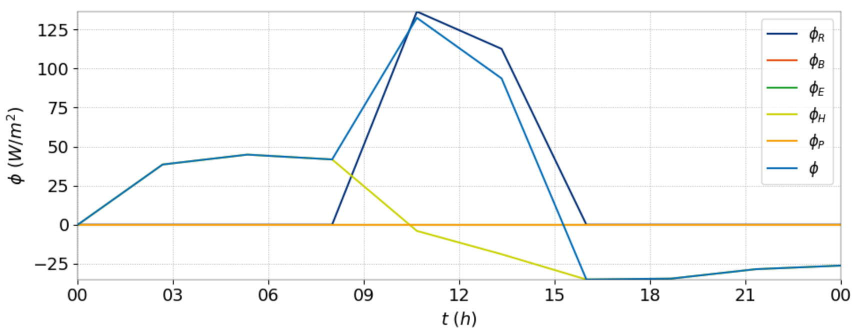



Figure 12.3: Thermal fluxes at the free surface with the default linear budget model

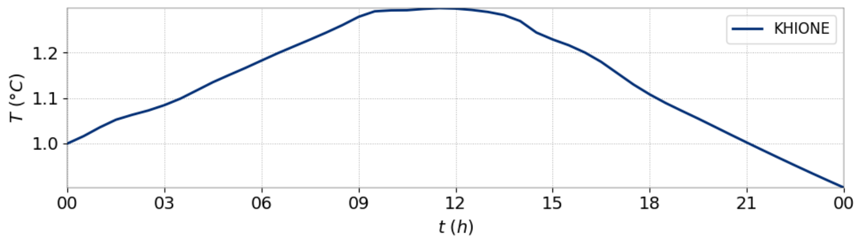



Figure 12.4: Evolution of the water temperature

The stratification of the temperature in the water column is shown on Figure 12.5 and 12.6. One can see that the flux is applied at the free surface boundary so the temperature is higher in the top of the water column at the middle of the simulation when the air is warming up the water. When the air is cooling down the water at the end of the simulation, its temperature is lower at the top of the water column.

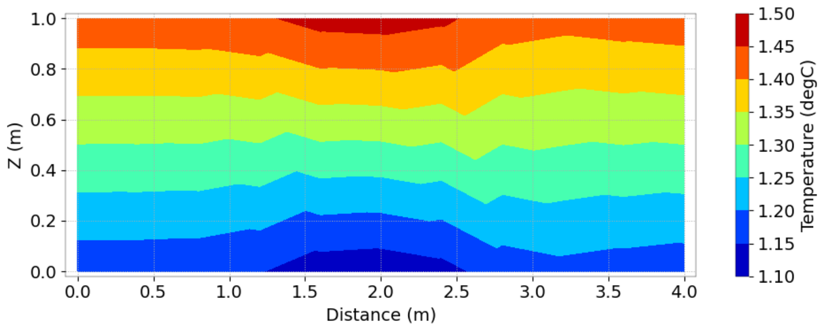



Figure 12.5: Vertical temperature distribution at the middle of the simulation

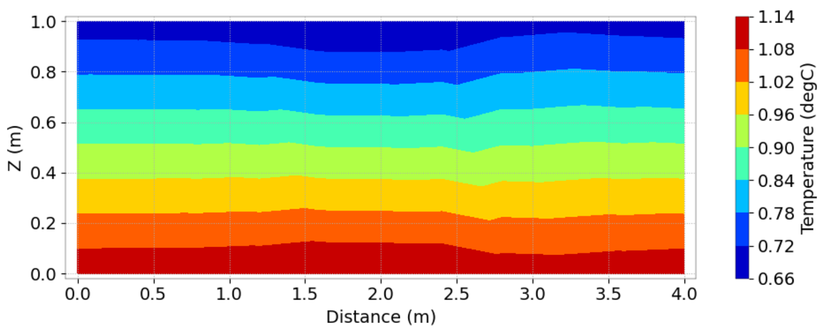



Figure 12.6: Vertical temperature distribution at the end of the simulation

## 12.4 Conclusions

The water remains at rest and the temperature evolves as a result of changes in the atmospheric conditions (air temperature, solar radiation, etc.). The model is also able to represent the vertical distribution of the temperature in the water column.

[1] T. Carstens. Experiments with supercooling and ice formation in flowing water. *Geofys. Publ. Norway*, 26(9)(3-18), 1966.

[2] T. O'D. Hanley and G. Tsang. Formation and properties of frazil in saline water. *Cold Regions Science and Technology*, 8:209–221, 1984.