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# Numerical modelling of air entrainment In hydraulic engineering

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## Numerical modelling of air entrainment

Develop a sub-grid model for air entrainment based on interFoam



(a) Stepped Spillway<sup>1</sup>



(b) Hydraulic Jump<sup>2</sup>

<sup>1</sup>Photo taken from [2]

<sup>2</sup>Photo taken from [1]

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### Numerical modelling of air entrainment

- Develop a sub-grid model for air entrainment based on interFoam
- Testing airInterFoam<sup>[4]</sup>





(a) Stepped Spillway<sup>3</sup>

(b) Hydraulic Jump<sup>4</sup>

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<sup>3</sup>Photo taken from [2]

<sup>4</sup>Photo taken from [1]

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Defining the concept				

### 1 Air entrainment

- Defining the concept
- State of the art
- airInterFoam

## 2 Stepped Spillway

- Inception point and surface elevation
- Dependence on inputvariables
- Void fraction

# 3 Hydraulic Jump

- Features
- Results

## 4 Conclusion



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Defining the concept				

### Air entrainment in free surface flow

Turbulent forces > surface forces + buoyancy forces





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State of the art				

State of the art

# Euler-Euler two fluid model

twoPhaseEulerFoam

Numerical diffusion at the interface for stratified flow

# Interface capturing methods

interFoam

Challenging to capture the processes at the surface

# Hybrid models

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# Subgrid models based on VoF

# Existing subgrid models based on VoF

Hirt 
$$(2003)^{[3]} \Rightarrow$$
 **FLOW-3D**

Lopes 
$$(2017)^{[4]} \Rightarrow$$
 airInterFoam

Due to lack of grid resolution, the amount of entrained air will be underestimated by the VoF method

# https://openfoamwiki.net/index.php/Contrib/airInterFoam

State of the art

Air entrainment	Stepped Spillway	Hydraulic Jump	Conclusion	References
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State of the art				

#### interFoam

Solves a single set of mass- and momentum equations

 $\nabla \boldsymbol{U} = \boldsymbol{0}$  $\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot (\rho \boldsymbol{U} \boldsymbol{U}) = -\nabla p^* + \mathbf{g} \cdot \mathbf{x} \nabla \rho + \nabla \cdot \boldsymbol{\tau} + \mathbf{f}$ 

 interFoam uses a VOF method with a compression term to capture the interface

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \boldsymbol{U}) + \nabla \cdot [\boldsymbol{U}_r \alpha (1 - \alpha)] = 0$$

where  $\boldsymbol{U}_r = \boldsymbol{U}_1 - \boldsymbol{U}_2$  is the relative velocity

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$$\frac{\partial \alpha_g}{\partial t} + \nabla \cdot (\mathbf{u}_g \alpha_g) - b \cdot \nabla \cdot (\nu_t \nabla \alpha_g) = S_g$$

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$$\begin{split} \frac{\partial \alpha_g}{\partial t} + \nabla \cdot \left( \mathbf{u}_g \alpha_g \right) - b \cdot \nabla \cdot \left( \nu_t \nabla \alpha_g \right) &= S_g \\ S_g &= \frac{a}{\phi_{ent}} \Big\langle \frac{\partial \mathbf{u}_n}{\partial \mathbf{n}} \Big\rangle \delta_{fs} \end{split}$$

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$$\frac{\partial \alpha_g}{\partial t} + \nabla \cdot (\mathbf{u}_g \alpha_g) - b \cdot \nabla \cdot (\nu_t \nabla \alpha_g) = S_g$$

$$S_g = \frac{a}{\phi_{ent}} \Big\langle \frac{\partial \mathbf{u}_n}{\partial \mathbf{n}} \Big\rangle \delta_{fs}$$

 $k > k_c, u > u_c$ 

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$$\frac{\partial \alpha_g}{\partial t} + \nabla \cdot (\mathbf{u}_g \alpha_g) - b \cdot \nabla \cdot (\nu_t \nabla \alpha_g) = S_g$$

$$S_g = \frac{a}{\phi_{ent}} \Big\langle \frac{\partial \mathbf{u}_n}{\partial \mathbf{n}} \Big\rangle \delta_{fs}$$

$$k > k_c, u > u_c$$

$$\mathbf{u}_g = \mathbf{u}_l + \mathbf{u}_r$$

Air entrainment	Stepped Spillway	Hydraulic Jump	Conclusion	References
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# • $\alpha_g$ is calculated

# $\blacksquare \alpha_l$ is calculated independent of $\alpha_g$

$$\alpha_2 = 1 - \alpha_l - \alpha_g$$

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Interacts with the  $\alpha_l$ -equation by reducing the compression

```
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  -fvc::flux(-phir, alpha2, alpharScheme),
  alpha1,
  alpharScheme
)
```

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#### airInterFoam

#### Test cases

Stepped spillwayHydraulic jump







(b) Hydraulic Jump<sup>6</sup>

<sup>5</sup>Photo taken from [2]

<sup>6</sup>Photo taken from [1]

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# Stepped Spillway



Sketch taken from [6]

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## Stepped Spillway



(a) Step 3



### (c) Step 5 (IP)



(d) Step 6



### (f) Step 8

Photos taken from [6]

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Stepped Spilly	way			
H= 1.68 m	and a start of the	28 steps Slope: 26.6°	Inception foun experime at 5th ste	n point d entally p edge
	airInterFoa been verifie • Inception po • Surface eleva	m and the Flow3D-mc d for this stepped spil int ation curve	odel has Iway	

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Dependence on inputvariables

### Dependent on inputvariables



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Dependence on inputvaria	ables			
Inception poir	nt and surface ele	evation		
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		<sup>a</sup> Sketo	h taken from [6]	

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Dependence on inputvariables	5			
Inception point	and surface elevat	ion growing turbulent boundary layer	nonaerated	
0.08 0.07 N 0.05 H 0.04 0.03 0.02 0.0 0.5	interFoam expdata	n_kc02	Stop Generation Now region wont of the stop of the sto	
		<sup>a</sup> Sketch take	n from [6]	

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#### Air entrainment 0 000

Void fraction

## Void fraction



Stepped Spillway

Conclusion 0 References 0



(a) Step 5



(b) Step 6



(c) Step 7

Photos taken from [6]

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Features				
Hydraulic Jump				
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Upstream jet -	$\rightarrow$ d	Turbulent s	hear region	Ś
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Figure: Hydraulic jump

	Sketch	taken	from	[7]
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Footures				

## Hydraulic Jump

- Void fraction profiles
- Velocity profiles
- Free surface contour

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# Hydraulic Jump

- Void fraction profiles
- Velocity profiles
- Free surface contour



Figure: Hydraulic jump

Sketch	taken	from	[7]
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Features				

# Test Case

- Froude number 4.8
- Physical experiments by Murzyn<sup>[5]</sup>, reproduced by Witt<sup>[7]</sup> using interFoam



Figure: Hydraulic jump

Sketch	taken	from	[7]
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#### Results

#### interFoam - reproduction



(a) Current work , realizableKE



	Stepped Spillway	Hydraulic Jump	Conclusion	References
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#### Results

### interFoam - realizableKE vs k- $\epsilon$







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Results				

#### $interFoam - k-\epsilon$



 $\Delta x = 0.005$ 

Toe placement = 25.2



 $\Delta x = 0.0025$ 

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	Stepped Spillway	Hydraulic Jump	Conclusion	References
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#### Results

#### interFoam – airInterFoam – $k-\epsilon$





#### $\Delta x=0.0025,\, {\rm interFoam}$



	Stepped Spillway	Hydraulic Jump	Conclusion	References
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#### Results

#### Dependence on parameters





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# Conclusion

- Using a local reduction in interface compression gave some air entrained into the flow
- Gave results close to the experimental for prediction of
  - Inception point
  - Surface elevation curve
  - Void fraction (at lower parts of the spillway)

# Sensitive to

- Grid refinement
- Input parameters

# Behavior of hydraulic jump sensitive to choice of turbulence model

• too little air transported in lower parts and towards the end of the jump

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References

## References I

- [1] J. Ball.
  - Hydraulic Jump.

Available at https://www.flickr.com/photos/jball359/6998692825, 2019-11-20.

[2] C. Gonzalez.

International symposium on hydraulic structures ciudad guayana, venezuela, october 2006 air entrainment and energy dissipation on embankment spillways. 11 2019.

- [3] C. Hirt. Modeling turbulent entrainment of air at a free surface. *Flow Science, Inc*, 2003.
- [4] P. Lopes, J. Leandro, and R. F. Carvalho. Self-aeration modelling using a sub-grid volume-of-fluid model. International Journal of Nonlinear Sciences and Numerical Simulation, 18(7-8), dec 2017.
- [5] F. Murzyn, D. Mouaze, and J. Chaplin. Optical fibre probe measurements of bubbly flow in hydraulic jumps. International Journal of Multiphase Flow, 31(1):141–154, jan 2005.
- [6] D. Valero and D. Bung. Hybrid investigation of air transport processes in moderately sloped stepped spillway flows. In E-proceedings of the 36th IAHR World Congress 28 June - 3 July, 2015, The Hague, the Netherlands, pages 1 – 10, 2015.
- [7] A. Witt, J. Gulliver, and L. Shen.
   Simulating air entrainment and vortex dynamics in a hydraulic jump. International Journal of Multiphase Flow, 72:165 – 180, 2015.

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