Título Combining Computational Fluid Dynamics and Dimensional Analysis in the Design of Oil Skimmer Tanks

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Combining Computational Fluid Dynamics and Dimensional Analysis in the Design of Oil Skimmer Tanks

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Problem

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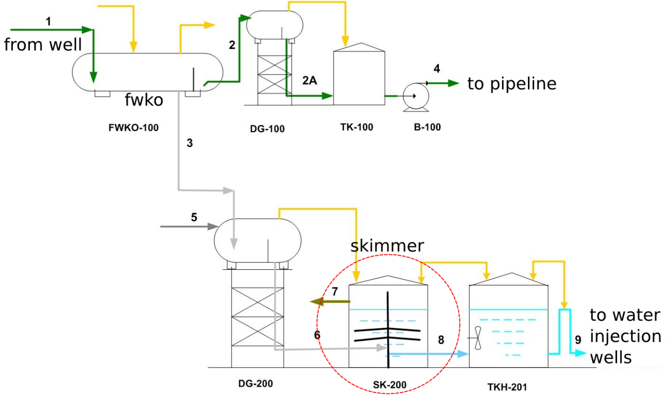
Oil treatment plant:



Our goal: evaluate *efficacy* of a skimmer (percent of oil removed)

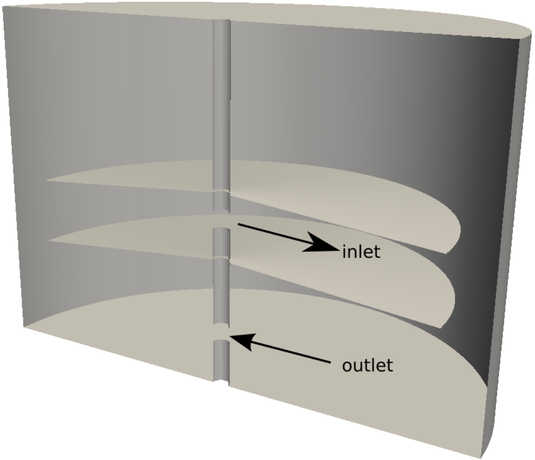
Problem

Skimmer tank

- Big gravity separators for cleaning water.
- Recovered oil is skimmed from the surface.
- Designed for target oil droplet radius r_d and flow rate Q
- Characteristic times:
  - residence time
    $t_r = \frac{V}{Q}$ (V: tank volume)
  - droplet rising time
    $t_d = \frac{H}{V_0}$ (H: tank height, V_0: rising velocity of a droplet of oil)

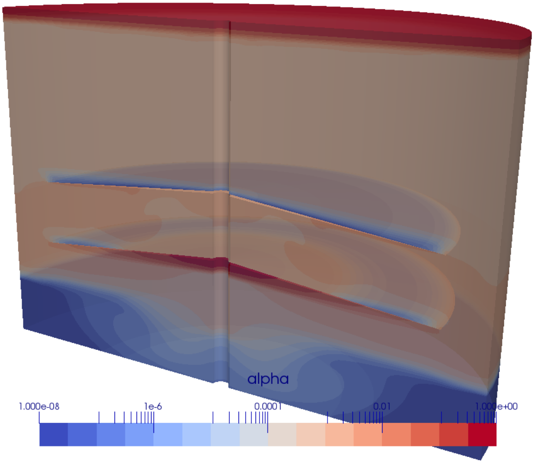
Problem

Skimmer tank: standard design



Problem

Skimmer tank: typical steady state (red=oil, blue=water)



Computational fluid Dynamics

- Mathematical model: Drift Flux
- Numerical model: Finite Volumes (OpenFOAM)
- Application: separationFoam
- Postprocessing: ParaView

CFD: Mathematical model

- Drift Flux Model, Ishii & Hibiki (based on the Two Fluid Model, Ishii 1987).
- The (oil-water) mixture is a single pseudo-fluid.
- Two phases: 1-continuous (water) and 2-disperse (oil).
- Diferential Equations:
  1. mixture continuity
  2. mixture momentum
  3. disperse phase transport
- Closure relation:
  4. drift velocity model

CFD: Mathematical model

- Main variables:
  - α_2 : volumetric fraction of oil
  - $\mathbf{v}_m$: center of mass (mixture) velocity
  - p_m : mixture pressure
  - $\mathbf{v}_{2j} = \mathbf{v}_2 - \mathbf{j}$: "drift" velocity of oil

  where
  - $\mathbf{j} = \alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2$: center of volume velocity
  - $\alpha_1 = 1 - \alpha_2$: volumetric fraction of water

CFD: Mathematical model

- Differential Equations:
  1. mixture continuity

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{v}_m) = 0$$

  2. mixture momentum

$$\frac{\partial \rho_m \mathbf{v}_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{v}_m \mathbf{v}_m) = - \nabla p_m + \nabla \cdot (\tau + \tau^t) - \nabla \cdot \left[\frac{\alpha_2 \rho_1 \rho_2}{(1-\alpha_2)\rho_m} \mathbf{v}_{2j} \mathbf{v}_{2j} \right] + \rho_m \mathbf{g}$$

  3. disperse phase transport

$$\frac{\partial \alpha_2 \rho_2}{\partial t} + \nabla \cdot (\alpha_2 \rho_2 \mathbf{v}_m) = -\nabla \cdot \left(\frac{\alpha_2 \rho_1 \rho_2}{\rho_m} \mathbf{v}_{2j} \right)$$

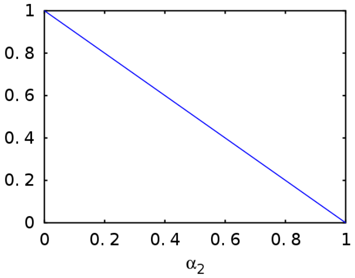
CFD: Mathematical model

- Closure relation:
  4. drift velocity model (monodisperse)

$$\mathbf{v}_{2j} = \mathbf{V}_0(1-\alpha_2)$$

where

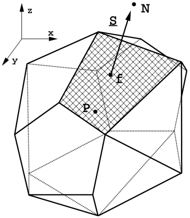
- $\mathbf{V}_0 = \frac{2}{9}\frac{g(\rho_1-\rho_2)r_d^2}{\mu_1}$ rising velocity of a droplet of oil
- $(1-\alpha_2)$: factor to model the hindering effect



CFD: Numerical model

UADE

- Method: Finite Volumes
- Package: Suite OpenFOAM (www.openfoam.org)
- Application: separationFoam (Larreteguy, Barceló, Caron)
- Based on settlingFoam (Brennan, 2001)
- Features of separationFoam 3.1 (2016)
  - model for the mixture viscosity
  - ensures realistic (bounded) solutions for volume fractions
  - strict mass conservation
  - thermal effects (i.e.: FWKO with fire tubes)
  - pressure gradient driven drift (i.e.: rotating flow separators)



Dimensional Analysis

DA

- Tool for reducing the set of n dimensional variables of a problem to a smaller set of k dimensionless ones.
- The dimensionless variables are referred to as π numbers.
- Theorem π of Buckingham:
$$x_n = \mathbf{f}(x_1, x_2, ..., x_{n-1}) \rightarrow \pi_k = \mathbf{f}'(\pi_1, ..., \pi_{k-1})$$
- Functions $\mathbf{f}$ and/or $\mathbf{f}'$ to be determined by theoretical analysis, experiments, or simulations.
- After aplying DA, less (much less) experiments/simulations are required.

DA: example

Example:

Pressure gradient $\frac{dp}{dx}$ in pipe flow depends on 5 variables

$$\frac{dp}{dx} = \mathbf{f}(\{V\}, \{\rho, \mu\}, \{e, D\})$$

where the subsets $\{V\}$, $\{\rho, \mu\}$ and $\{e, D\}$ refer to operational, physical, and geometric variables.

DA allows us to rewrite this using less dimensionless variables as

$$f = \mathbf{f}'(Re_D, \epsilon)$$

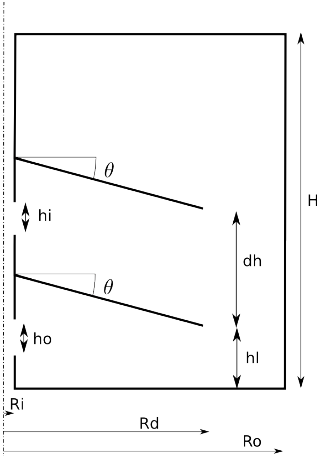
where

- $f = -\frac{dp}{dx} D/(\frac{1}{2}\rho V^2)$ friction factor
- $Re_D = \frac{\rho V D}{\mu}$ Reynolds number
- $\epsilon = \frac{e}{D}$ relative rugosity

DA: model of a skimmer

Skimmer

- Subset of geometric variables
  - Standard design: vertical cylinder with a pair of inclined dishes.
  - Inlet and outlet assumed centered.
  - Size and shape defined by subset $\mathbf{g} = \{H, R_i, R_d, R_o, h_i, h_o, h_l, d_h, \theta\}$
- Subset of physical parameters
  - Densities and viscosities of both fluids, and gravity acceleration
    $\mathbf{p} = \{\rho_1, \mu_1, \rho_2, \mu_2, g\}$



DA: model of a skimmer

- Subset of operational conditions
  - Process assumed to depend on

$$\mathbf{o} = \{\alpha_i, Q, r_d\}$$

where
- α_i: inlet fraction of oil,
- Q: flow rate, and
- r_d: oil droplet radius.

We propose then the efficacy e to depend on 17 variables

$$e = \mathbf{f}(\{\alpha_i, Q, r_d\}, \{\rho_1, \mu_1, \rho_2, \mu_2, g\}, \{H, R_i, R_d, R_o, ..., \theta\})$$

or with the subset notation

$$e = \mathbf{f}(\mathbf{o}, \mathbf{p}, \mathbf{g})$$

DA: model of a skimmer

By applying DA we are able to reduce in 3 the number of variables. We propose the following:

- Reduce in 1 the subset **g** by selecting H as reference
$$\mathbf{g}' = \{\frac{R_i}{H}, \frac{R_d}{H}, .., \theta\}$$
- Reduce in 2 the combination of the operational and physical subsets **o** and **p** by defining the dimensionless subset
$$\mathbf{q}' = \{\alpha_i, Ri, ReRi^{\frac{1}{2}}, t'_d, \frac{\rho_1}{\rho_2}, \frac{\mu_1}{\mu_2}\}$$
where
  - $Re = \frac{\rho_1 Q}{\mu_1 H}$: Reynolds number
  - $Ri = g\alpha_i(1 - \frac{\rho_2}{\rho_1})\frac{H^5}{Q^2}$: Richardson number
  - $t'_d = \frac{t_d}{t_r} = \frac{9\mu_1 Q}{2g(\rho_1 - \rho_2) r_d^2 H^2}$: relative droplet rising time

DA: model of a skimmer

- Note: $ReRi^{\frac{1}{2}}$ selected instead of Re because the product does not depend on Q

$$ReRi^{\frac{1}{2}} = \frac{\sqrt{g\alpha_i\rho_1(\rho_1-\rho_2)}}{\mu_1}H^{\frac{3}{2}}$$

Therefore, e depends on 14 dimensionless variables

$$e = \mathbf{f}'(\{\alpha_i, Ri, ReRi^{\frac{1}{2}}, t'_d, \frac{\rho_1}{\rho_2}, \frac{\mu_1}{\mu_2}\}, \{\frac{R_i}{H}, \frac{R_d}{H}, .., \theta\})$$

or with the subset notation

$$e = \mathbf{f}'(\mathbf{q}', \mathbf{g}')$$

Results

Simulation stages

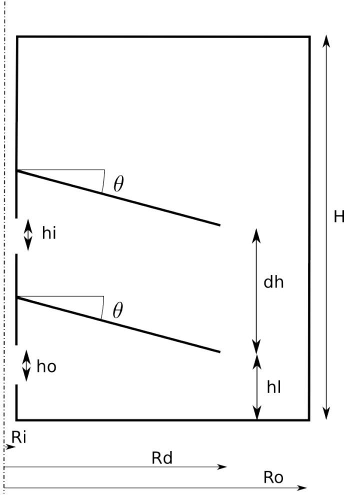
1. Run a reference case.
2. Run cases to verify that e is constant for fixed $\mathbf{q}'$ and $\mathbf{g}'$.
3. Run a sensitivity analisis to build the desired response surface function.

Results: 1) reference

The shape is defined by the subset $\mathbf{g}'$

Variable	Value
R_i/H	0.0250
R_d/H	0.6250
R_o/H	0.7500
h_i/H	0.0500
h_o/H	0.0500
h_l/H	0.3125
d_h/H	0.1250
θ	0.0873

Height is set to $H = 8m$.



Results: 1) reference

The physical properties subset **p** is

Variable	Value
ρ_1	$1000 kg/m^3$
ρ_2	$900 kg/m^3$
μ_1	$0.001 Pas$
μ_2	$0.020 Pas$
g	$9.81 m^2/s$

and the operational subset **o**

Variable	Value
α_i	$1000 ppm$
H	$8 m$
Q	$10000 m^3/d$
r_d	$75 \mu m$

Results: 1) reference

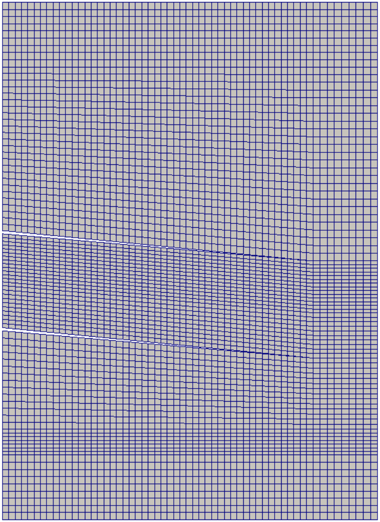
Therefore, the subset $\mathbf{q}'$ is

Variable	Value
α_i	$1e^{-3}$
t'_d	0.83
Ri	2400
$ReRi^{\frac{1}{2}}$	708712
ρ_1/ρ_2	10/9
μ_1/μ_2	1/20

Results: 1) reference

Simulation details

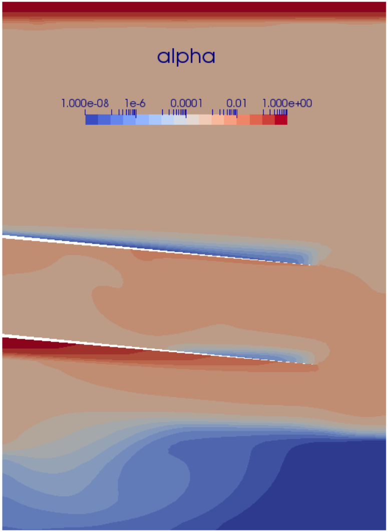
- mesh: structured, axisymmetric, 5104 cells, no layers
- runs: transients towards a "steady state", runTime=$20t_r$
- initial conditions: clean tank



Results: 1) reference

"Steady state" solution:

- Run time
  44 hs ($20t_r$)
- Efficacy
  $e = 83.7\%$



Results: 2) verification

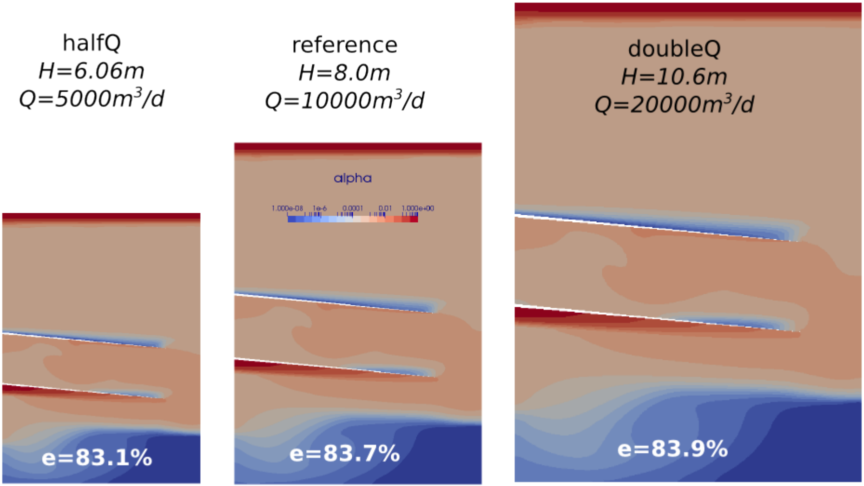
As an example of verification consider 3 cases with different Q, H, r_d, μ_1 and μ_2 but same dimensionless subsets $\mathbf{q}'$ and $\mathbf{g}'$.

CaseName	$Q[m^3/d]$	$H[m]$	$r_d[\mu m]$	$\mu_1[Pas]$	$\mu_2[Pas]$	runTime[hs]
halfQ	5000	6,06	57	0,000660	0,013195	38
reference	10000	8,00	75	0,001000	0,020000	44
doubleQ	20000	10,60	99	0,001516	0,030314	50

The three cases should result in the "same" efficacy.

Results: 2) verification

Oil fraction field and efficacy at $t = 20tr$. Verification OK $\surd$.



Results: 3) sensitivity analysis

The task:

- Evaluate the efficacy e of a given design under variations in the Ri and t'_d numbers, that is
$$e = \mathbf{f}'(R_i, t'_d),$$
while keeping the rest of the dimensionless numbers fixed.
- A given design means that the dimensionless subset $\mathbf{g}'$ is fixed.
- As for the remaining dimensionless numbers, we chose to fix
  - the size ot the tank (H),
  - the fluids ($\rho_1, \mu_1, \rho_2, \mu_2$),
  - the inlet oil fraction (α_i), and
  - the "planet" (g),

  to the reference values, and vary
  - the flow rate (Q), and
  - the target droplet radius (r_d).

Results: 3) sensitivity analysis

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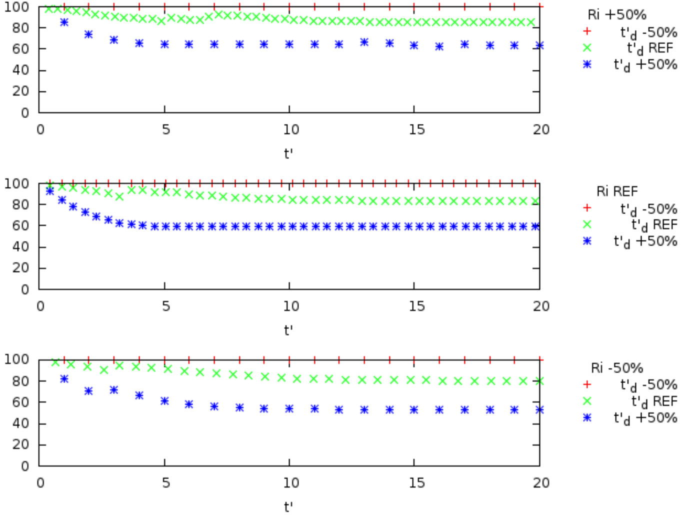
Cases: Ri and t'_d modified ±50% and ±25% from reference

CaseName	$Q[m^3/d]$	$r_d[\mu m]$	t'_d	Ri	runTime[hs]
CtREF-RiREF	10000	75	0,84	2400	44
CtP50-RiREF	10000	61	1,25	2400	44
CtP25-RiREF	10000	67	1,04	2400	44
CtM25-RiREF	10000	86	0,63	2400	44
CtM50-RiREF	10000	106	0,42	2400	44
CtREF-RiP50	8200	68	0,84	3600	53
CtREF-RiP25	9000	71	0,84	3000	49
CtREF-RiM25	11500	80	0,84	1800	38
CtREF-RiM50	14000	89	0,84	1200	32
CtP50-RiP50	8200	56	1,25	3600	53
CtP25-RiP50	8200	61	1,04	3600	53
CtM25-RiP50	8200	79	0,63	3600	53
CtM50-RiP50	8200	96	0,42	3600	53
CtP50-RiP25	9000	58	1,25	3000	49
CtP25-RiP25	9000	64	1,04	3000	49
CtM25-RiP25	9000	81	0,63	3000	49
CtM50-RiP25	9000	100	0,43	3000	49
CtP50-RiM25	11500	66	1,25	1800	38
CtP25-RiM25	11500	72	1,04	1800	38
CtM25-RiM25	11500	92	0,63	1800	38
CtM50-RiM25	11500	113	0,42	1800	38
CtP50-RiM50	14000	73	1,25	1200	32
CtP25-RiM50	14000	80	1,04	1200	32
CtM25-RiM50	14000	102	0,63	1200	32
CtM50-RiM50	14000	125	0,42	1200	32

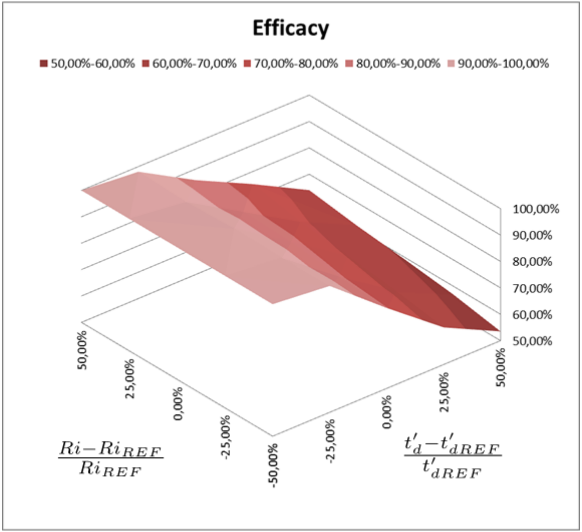
Results: 3) sensitivity analysis

Time evolution of efficacy $e(t')$ for selected cases, in %



Results: 3) sensitivity analysis

Steady state efficacy response surface



- Faster droplets → high efficacy for all *Ri*.
- Slower droplets → efficacy increases *slowly* with *Ri*.

Conclusions

- CFD and DA were combined for analysing the behaviour and performance of skimmer tanks for oil-water separation.
- A set of dimensionless variables was proposed and showed to represent the separation process under study.
- As a practical example, a standard design of a skimmer was tested under certain simplifying assumptions.
- The technique may provide important information on the role that the variables play in the performance of the tank.

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