COMSOL CONFERENCE 2014 CAMBRIDGE

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Numerical Modeling of Sampling Airborne Radioactive Particles Methods from the Stacks of Nuclear Facilities in Compliance with ISO 2889

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Presentation outline

- Introduction
- Sampling scheme
- ISO 2889 requirements
- Computational domain and mesh
- Governing equations
- Li&Ahmadi model for particle-surface interactions
- Computational Strategy
- Results
- Conclusions

Introduction

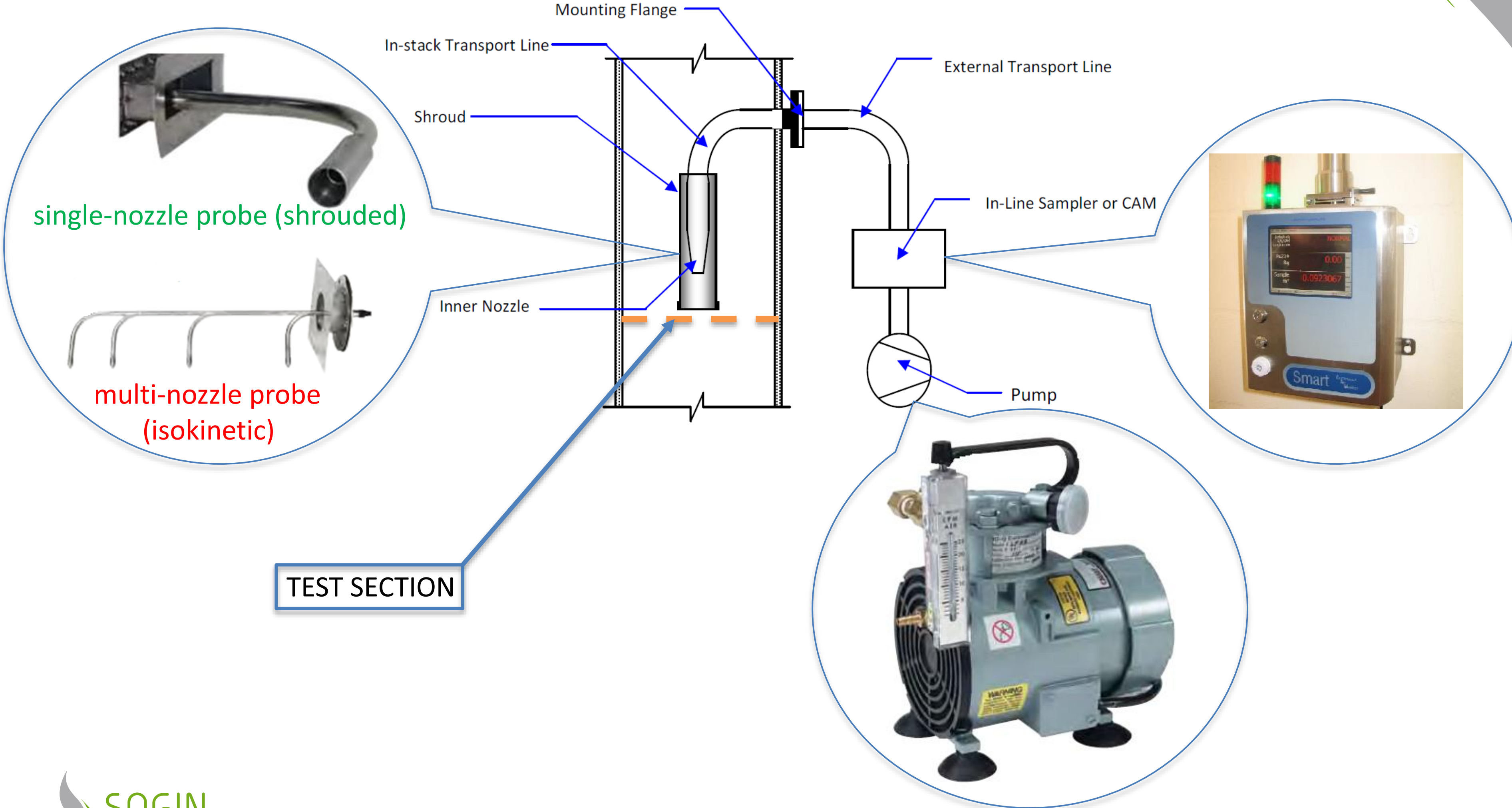
Nuclear facilities discharge the **off-gas** into the atmosphere and suitable monitoring and recording systems are required to protect the environment, workers and surrounding public.

The amount of **radioactive substances** (activity concentration) released from the stack has to be measured. A known sample amount (mass flow) is withdrawn from the stack and analyzed by Continuous Air Monitoring system. The **ISO 2889** sets the performance criteria and recommendations required for obtaining valid measurements.

The numerical study is performed in order to:

- determine if a preliminary stack design meets the requirements of ISO 2889 under nominal and reduced exhaust flow conditions (fire scenario) and particle aerodynamic diameter modifications (HEPA filter disruption);
- obtain indications about the geometrical and fluidynamical design for well mixed stream (one point sampling);
- reduce the design and field costs for future project using the similarity laws.

Sampling scheme



ISO 2889 requirements

ISO 2889:2010(E)

6.2.5 Summary of recommendations for locations to extract samples from a well mixed air stream

The recommended characteristics for locations from which to extract samples from a well mixed air stream are summarized in Table 1.

Table 1 — Summary of recommendations for a sampling location

Characteristic	Methodology	Recommendations
Measurement to determine if flow in a stack or duct is cyclonic	ISO 10780	The average resultant angle should be less than 20°.
Velocity profile	Selection of points across a section based on the guidance in ISO 10780 for the centre 2/3 of the area of the stack or duct. Additional points or area may be added to adequately cover the region.	COV should not exceed 20 % over the centre region of the stack that encompasses at least 2/3 of the stack cross-sectional area.
Tracer gas concentration profiles	Selection of points across a section based on the guidance in ISO 10780 for the centre 2/3 of the area of the stack or duct. Additional points or area may be added to adequately cover the region.	COV should not exceed 20 % over the centre region of the stack that encompasses at least 2/3 of the stack cross-sectional area.
Maximum tracer gas concentration deviations	Selection of points across a section based on the guidance in ISO 10780 for the entire cross-sectional area.	At no point on the measurement grid should the tracer gas concentration differ from the mean value by more than 30 %.
Aerosol particle concentration profile	Selection of points across a section based on the guidance in ISO 10780. Additional points or area may be added to adequately cover the region.	COV should not exceed 20 % over the centre region of the stack that encompasses at least 2/3 of the stack cross-sectional area. (*)

(*) PARTICLE AERODYNAMIC DIAMETER RECCOMENDED: 10 micron

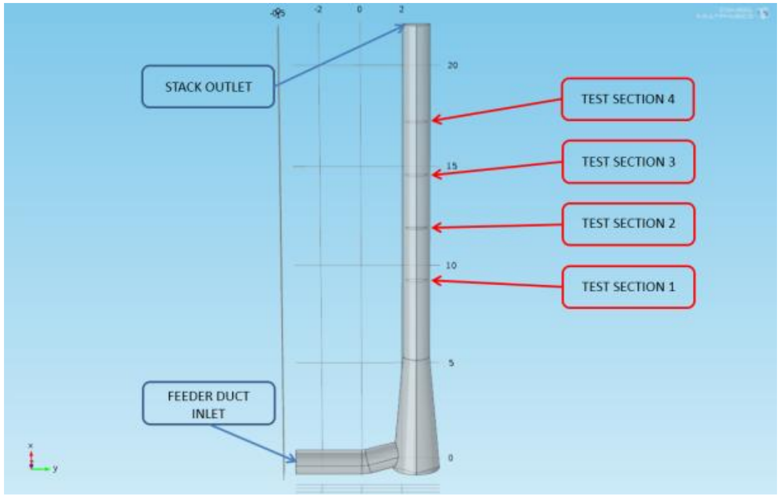
$$COV = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}}{\frac{1}{n}\sum_{i=1}^{n} x_i}$$

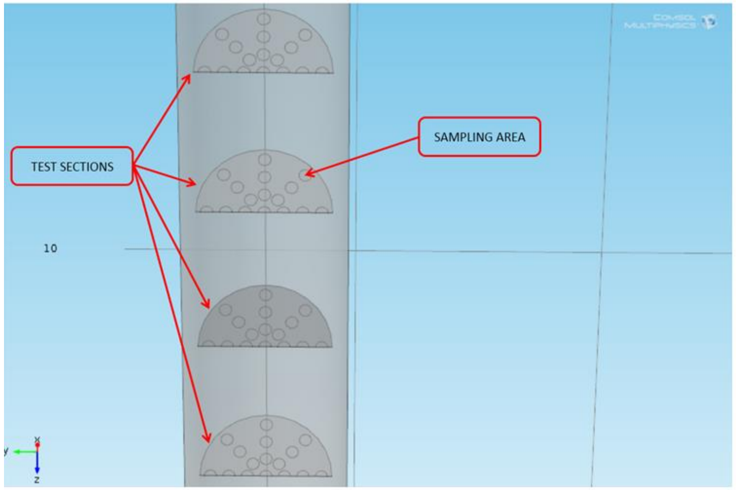
When well mixed conditions are achieved the sampling probe may contain a single nozzle, in other cases a multi-nozzle probe may be used or can be required to get a representative sample

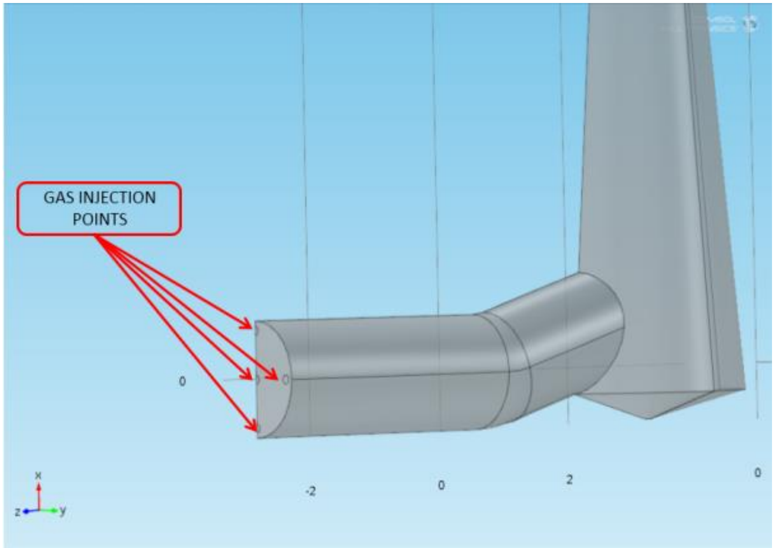
Table 2 — Number of nozzles for multi-nozzle sampling probes

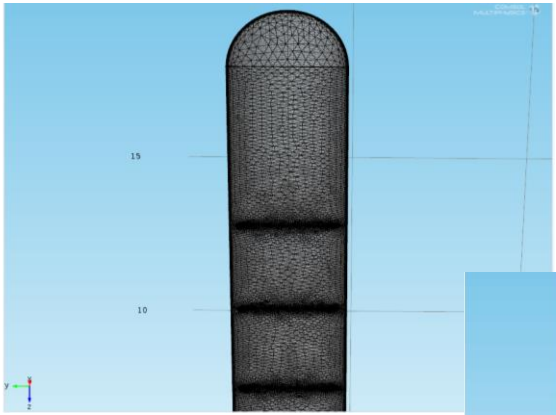
Stack or duct diameter mm	Number of nozzles
< 300	2
300 to 1 000	3 to 5
> 1 000	6 or more

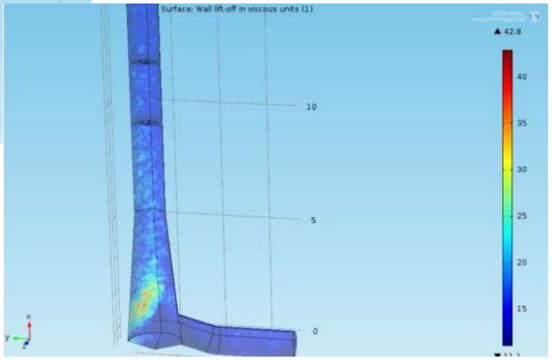
Computational domain and mesh











Governing equations

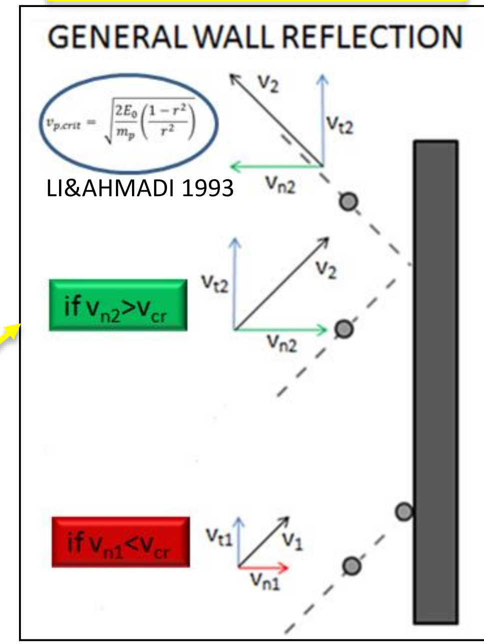
Mass conservation: $$\nabla \cdot \boldsymbol{u} = 0$$

Navier Stokes: $$\rho \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot [-p\boldsymbol{I} + \boldsymbol{\tau}]$$

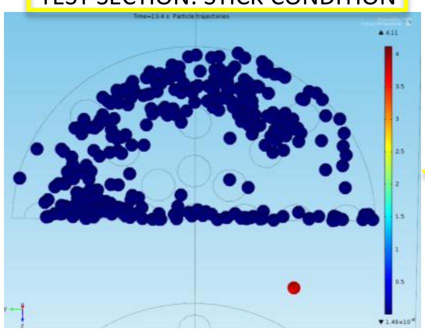
Chemical transport: $$\frac{\partial c}{\partial t} + \boldsymbol{u} \cdot \nabla c = \nabla \cdot (D \nabla c)$$

Newton's law for particles trajectories: $$\frac{d}{dt}(m_p \boldsymbol{v}) = \left(\frac{1}{\tau_p}\right) m_p(\boldsymbol{u} - \boldsymbol{v}) + m_p \boldsymbol{g} \frac{(\rho_p - \rho)}{\rho_p}$$

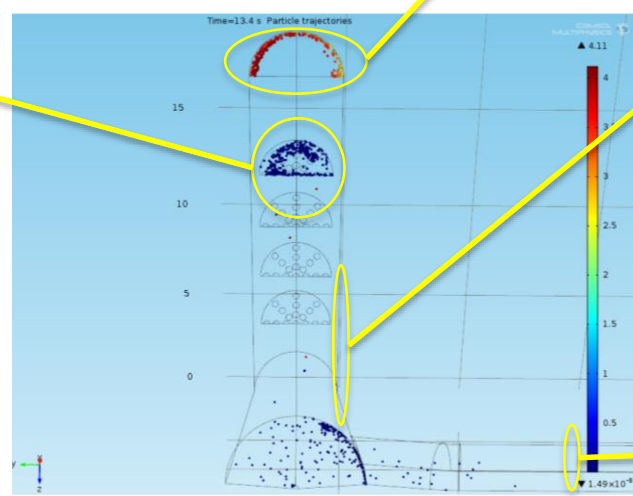
STACK WALLS: GENERAL REFLECTION



TEST SECTION: STICK CONDITION



OUTLET: FREEZE CONDITION



INLET: UNIFORM DISTRIBUITION

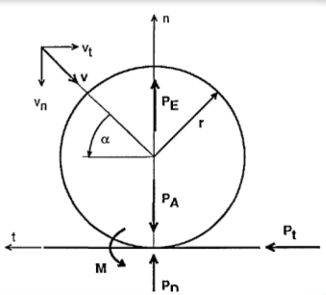
Li&Ahmadi model (1993)

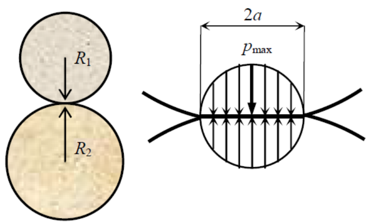
The main forces that contribute to particle adhesion on the walls are:

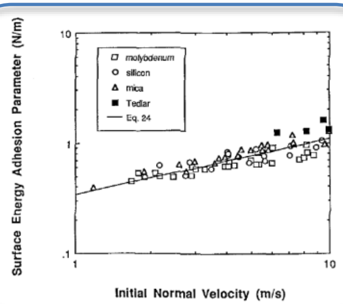
- **Van der Waals force** (molecular interactions between solid surfaces);
- Electrostatic force (caused by electrically charged particles);
- Liquid bridge force (caused by formation of liquid bridge).

The model is developed by combining the concepts of:

- Classical impact theory (equilibrium of force and angular momentum);
- Hertzian mechanics of elastic spheres;
- Contact surface adhesion energy (experimental data).







$$v_{p,crit} = \sqrt{\frac{2E_0}{m_p}\left(\frac{1-r^2}{r^2}\right)}$$

where r is the coefficient of restitution, m_p is the particle's mass and $E0$ is a coefficient that depends on elastic properties of materials and surface energy adhesion parameters

Computational strategy

FLUIDYNAMICAL SIMULATION

COMSOL MODULE: HEAT TRANSFER

TYPE: STATIONARY

MODEL: TURBULENT FLOW K-EPS (WALL FUNCTION)

SOLVER: DIRECT, SEGREGATED, MUMPS

MASS FLOW: 100% & 55%

SEGREGATED APPROACH

CHEMICAL SIMULATION

COMSOL MODULE: COMSOL MULTIPHYSICS

TYPE: STATIONARY

STABILIZATION: STREAMLINE AND CROSSWIND (DO CARMO-GALEAO)

SOLVER: DIRECT, SEGREGATED, MUMPS

GAS: HELIUM

PARTICLE TRACING SIMULATION

COMSOL MODULE: PARTICLE TRACING

TYPE: TRANSIENT

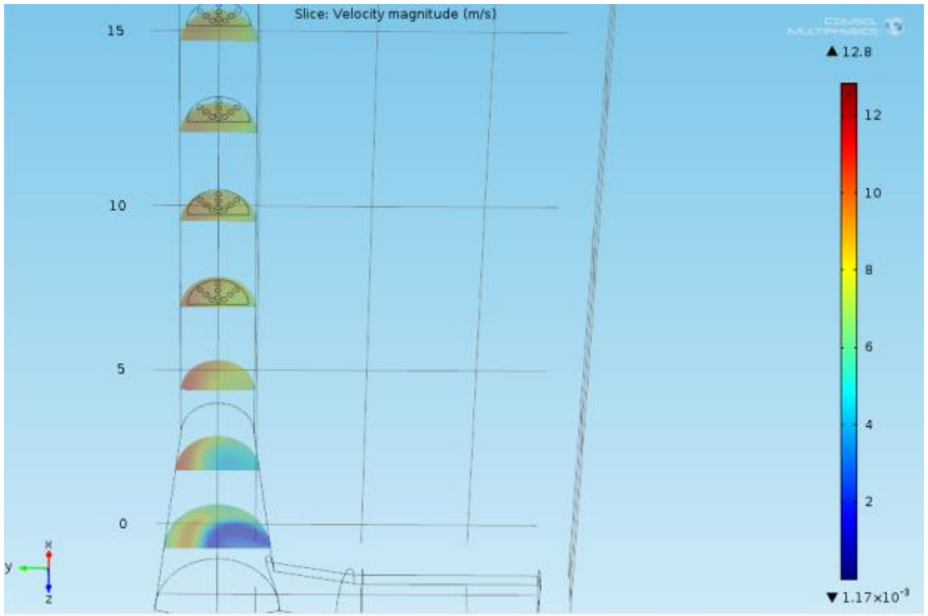
MODEL: SCHILLER-NAUMANN DRAG LAW + GRAVITY FORCE

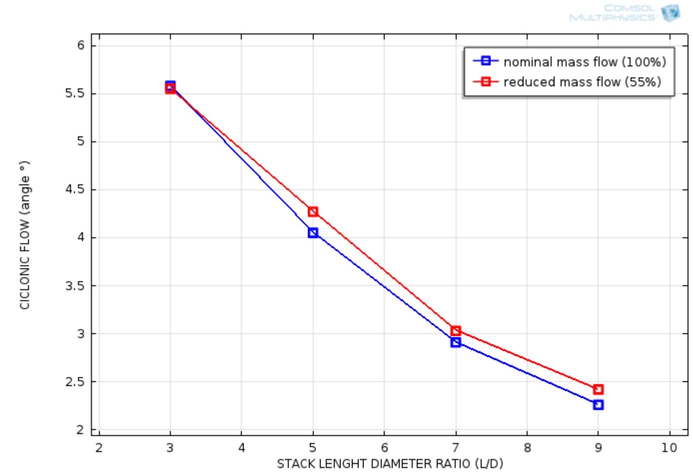
SOLVER: DIRECT, MUMPS, FULLY-COUPLED SOLVER

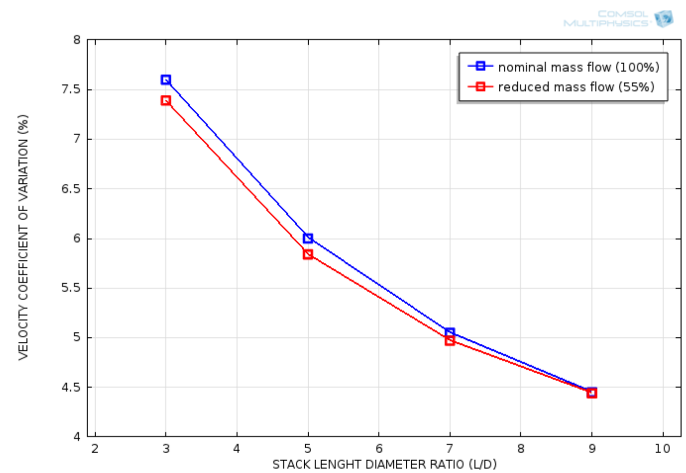
PARTICLE DIAMETER: 10-20-100 micron

Results (1/3): fluidynamical test

velocity field (100% flow):





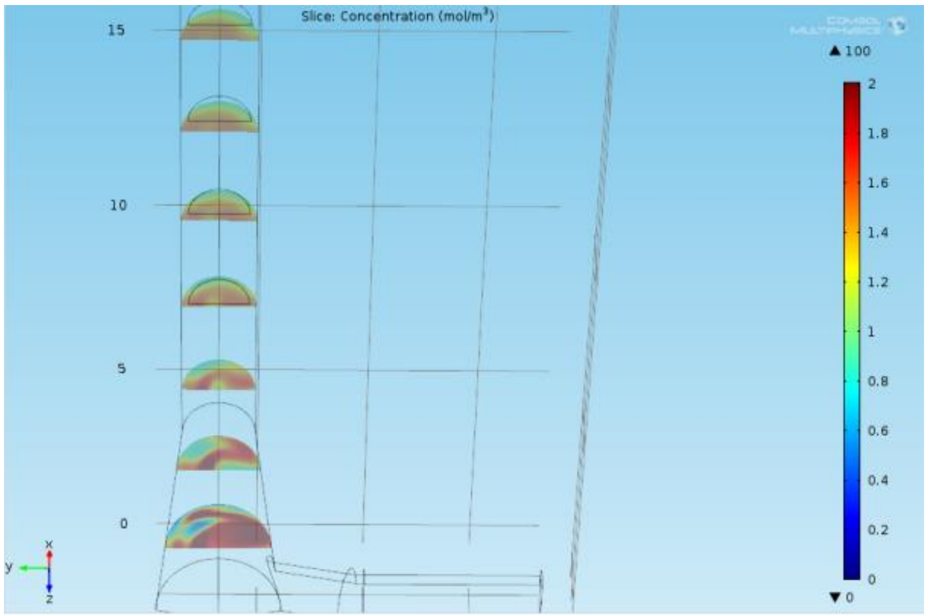


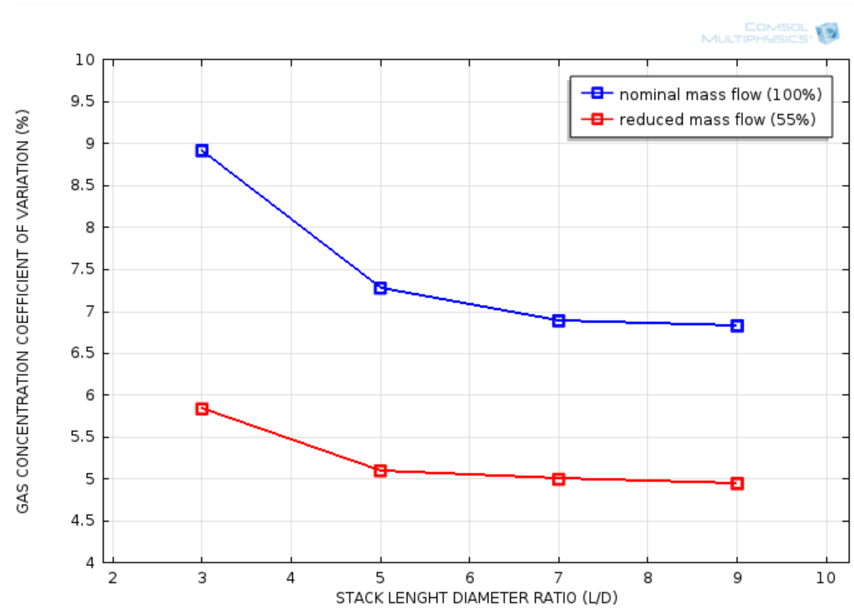
Test results:

- ✓ the cyclonic flow angle is less than 20° for each test section an mass flow studied;
- ✓ the velocity COV doesn’t exceed 20% for each test section an mass flow studied.

Results (2/3): chemical test

Gas concentration field (100% flow):



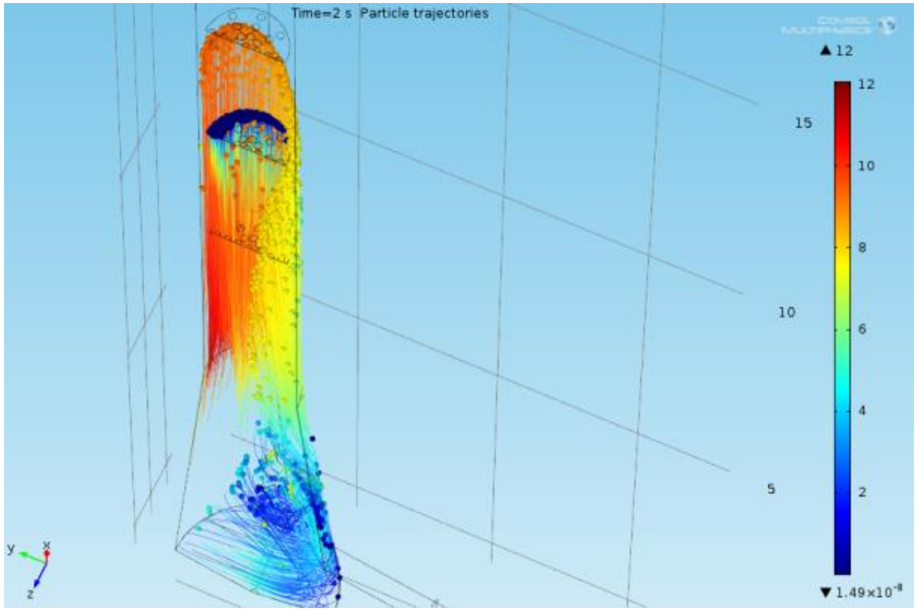


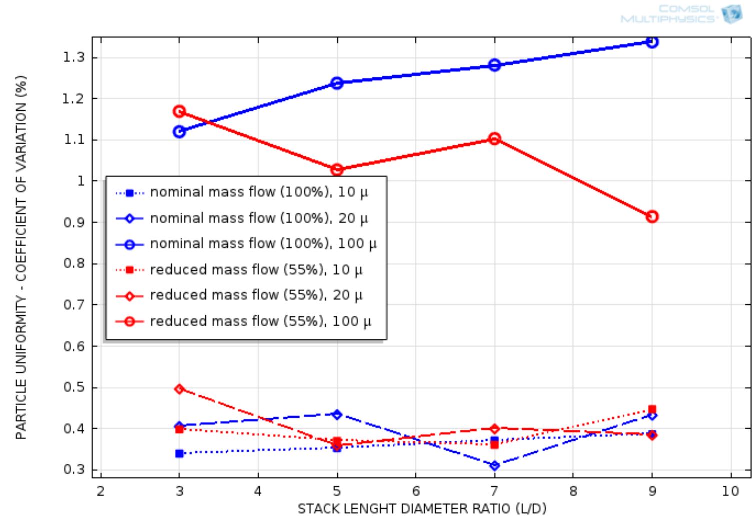
Test results:

- ✓ at no point on the test sections the concentration differs from the mean value by more than 30% for each test section and mass flow studied;
- ✓ the tracer gas COV doesn't exceed 20% for each test section and mass flow studied.

Results (3/3): particle test

Particle trajectories at time t=2s for 10 micron diameter and nominal flow rate (test section n.1):





Test results:

- the particle concentration COV exceeds 20% for each test section, mass flow and aerodynamic diameter studied;
- multiple nozzles are required.

ADDITIONAL STUDY: Percent of particles those stick on the boundaries and pass through test section n.4 for different flow rate and aerodynamic diameter

Case study	Stick particles	Sampling particles	Other
100% flow, 10 µ	4,2%	63.9%	31,9%
100% flow, 20 µ	4,9%	62,1%	33,0%
100% flow, 100 µ	32,5%	31,8%	35,7%
55% flow, 10 µ	4,5%	63,4%	32,1%
55% flow, 20 µ	5,3%	62,6%	32,1%
55% flow, 100 µ	44,2%	31,9%	23,9%

Conclusions

- all the ISO requirements are met except for aerosol well-mixed distribution test;
- are obtained useful indications about the sampling system performance during off design conditions (mass flow and aerodynamic diameter modifications);
- the preliminary stack design required a multi nozzles probe sampling system;
- future studies will be performed to evaluate the impact of feeder duct angle variations and mixing elements introduction in order to achieve the well mixed conditions (one nozzle sampling probe).

Thank you for your attention!

COV calculation spreadsheet

selection → Total number of particle in selection

CALCOLO COVARIANZA PARTICELLE_ESEMPIO - Excel

AREA	N. OF PARTICLES	N. OF PARTICLES (SIMMETRY)	MEAN SQUARED ERROR
1	5	10	1,12890625
2	5	10	1,12890625
3	9	18	48,12890625
4	6	6	25,62890625
5	9	9	4,25390625
6	10	10	1,12890625
7	10	10	1,12890625
8	10	10	1,12890625
9	12	12	0,87890625
10	15	15	15,50390625
11	9	9	4,25390625
12	4	4	49,87890625
13	7	14	8,62890625
14	9	18	48,12890625
15	7	14	8,62890625
16	4	8	9,37890625

MEAN CONCENTRATION	11,0625
STANDARD DEVIATION	3,906725
COV	0,35315

$$COV = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i-\bar{x})^2}}{\frac{1}{n}\sum_{i=1}^{n}x_i}$$