

A physics informed response model for calculation of flammable cloud volume based on computational fluid dynamics

**Sávio Vianna
University of Campinas
10th of May 2023 - P2SAC Conference - Purdue University**

Sávio S.V. Vianna

University of Campinas - Unicamp



- PhD University of Cambridge, UK
 - MSc. Coppe - UFRJ
 - Chemical Engineering - UFRJ
-
- DnV - Det Norske Veritas
 - Associate Professor - University of Campinas - Unicamp
 - Editor Journal of Loss Prevention in the Process Industries (CFD applied to process safety)
 - Editor Brazilian Journal of Chemical Engineering (Transport phenomena)

Motivation

- Things can go wrong
- Flammable cloud volumes depends on many factors
- Some of these factors are stochastic
- The volume of flammable clouds is not easy to predict
- And yet, how can we calculate reliable cloud volumes?



Contents

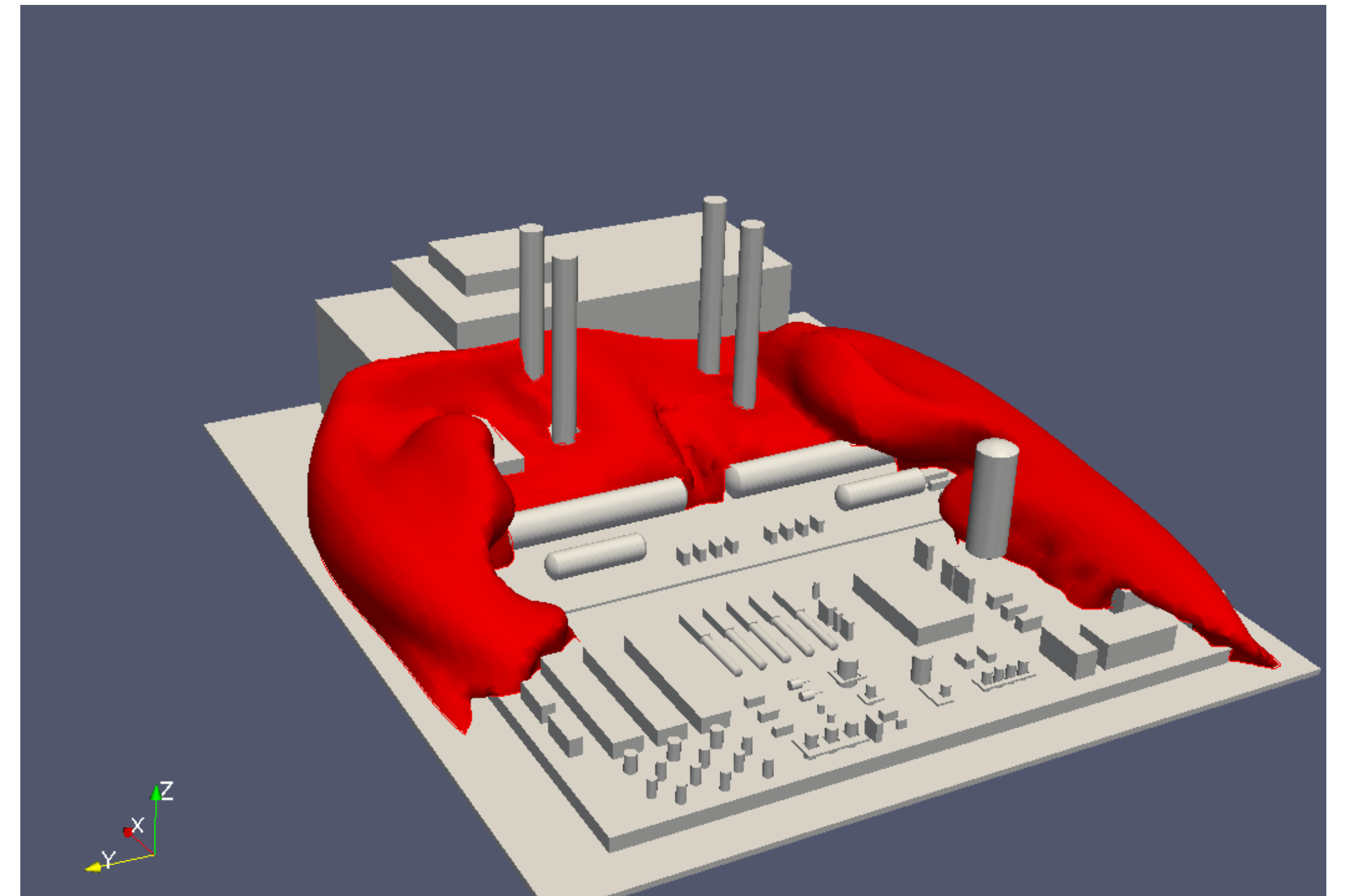


- Introduction
- Methodology
- Results
- Closing remarks

Introduction

Flammable cloud volume depends on:

- Material released
- Wind speed
- Wind direction
- Leak rate
- Geometry

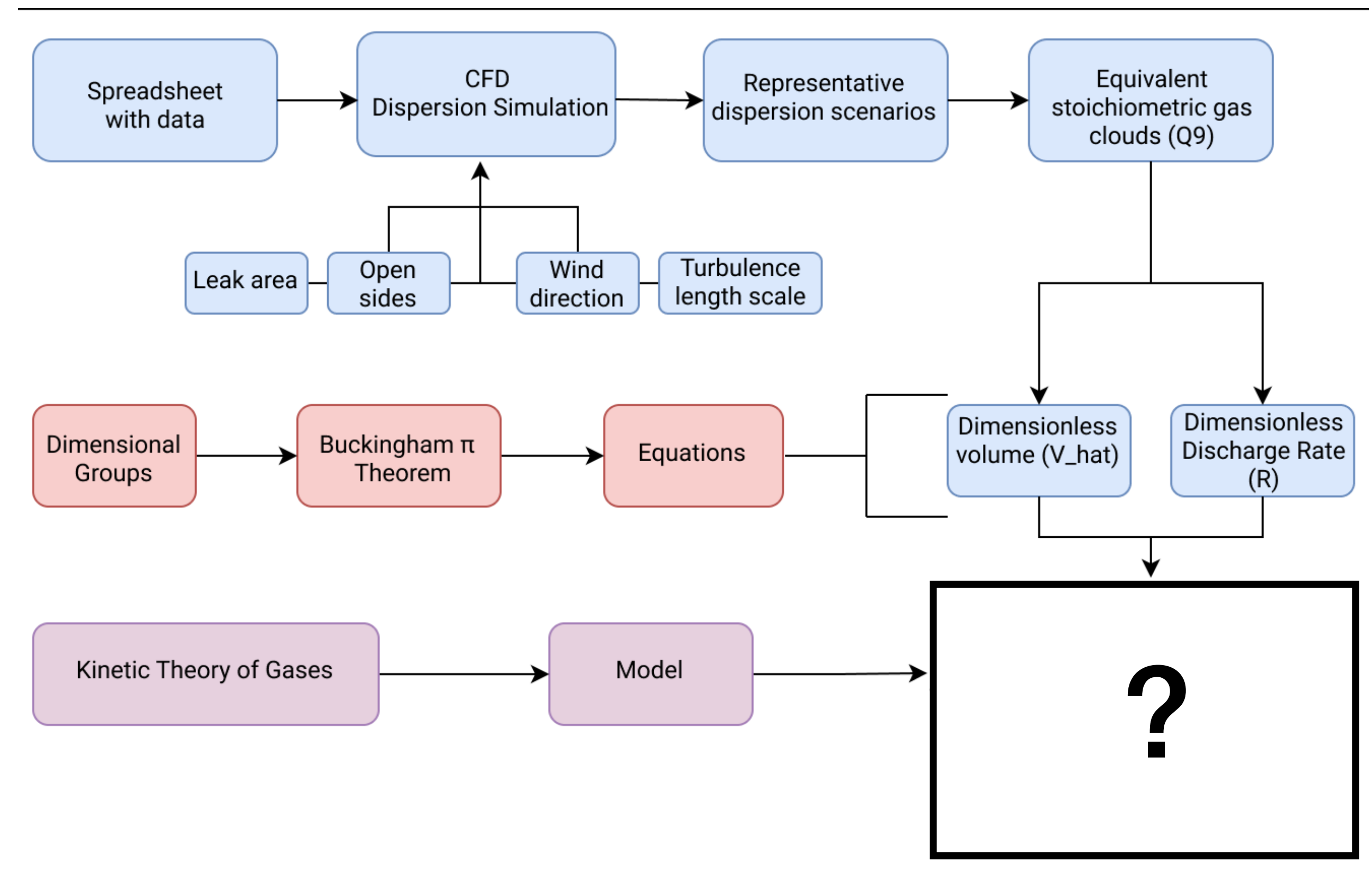


$$V_f = f(\rho, u, \dot{m}, L)$$

Methodology



- Reduce the number of variables via dimensional analysis
- Run simulations to verify whether there is a relation between the non-dimensional numbers
- Development of a model based on the kinetic theory of gases
- Validate the model
- Case study



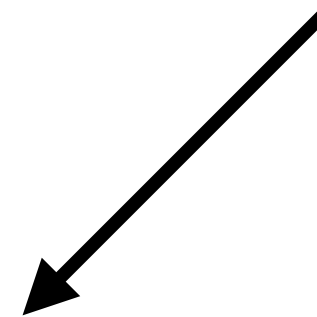
Results



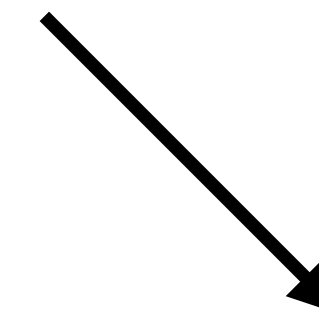
$$V_f = f(\rho, u, \dot{m}, L)$$



Buckingham theorem



$$\pi_1 = \frac{\dot{m}}{\rho Q}$$



$$\pi_1 = \frac{u^{1.5} \rho^{1.5} V_f}{\dot{m}^{1.5}}$$

Results



Is there any relation between the non-dimensional leak rate and the non-dimensional cloud size ?

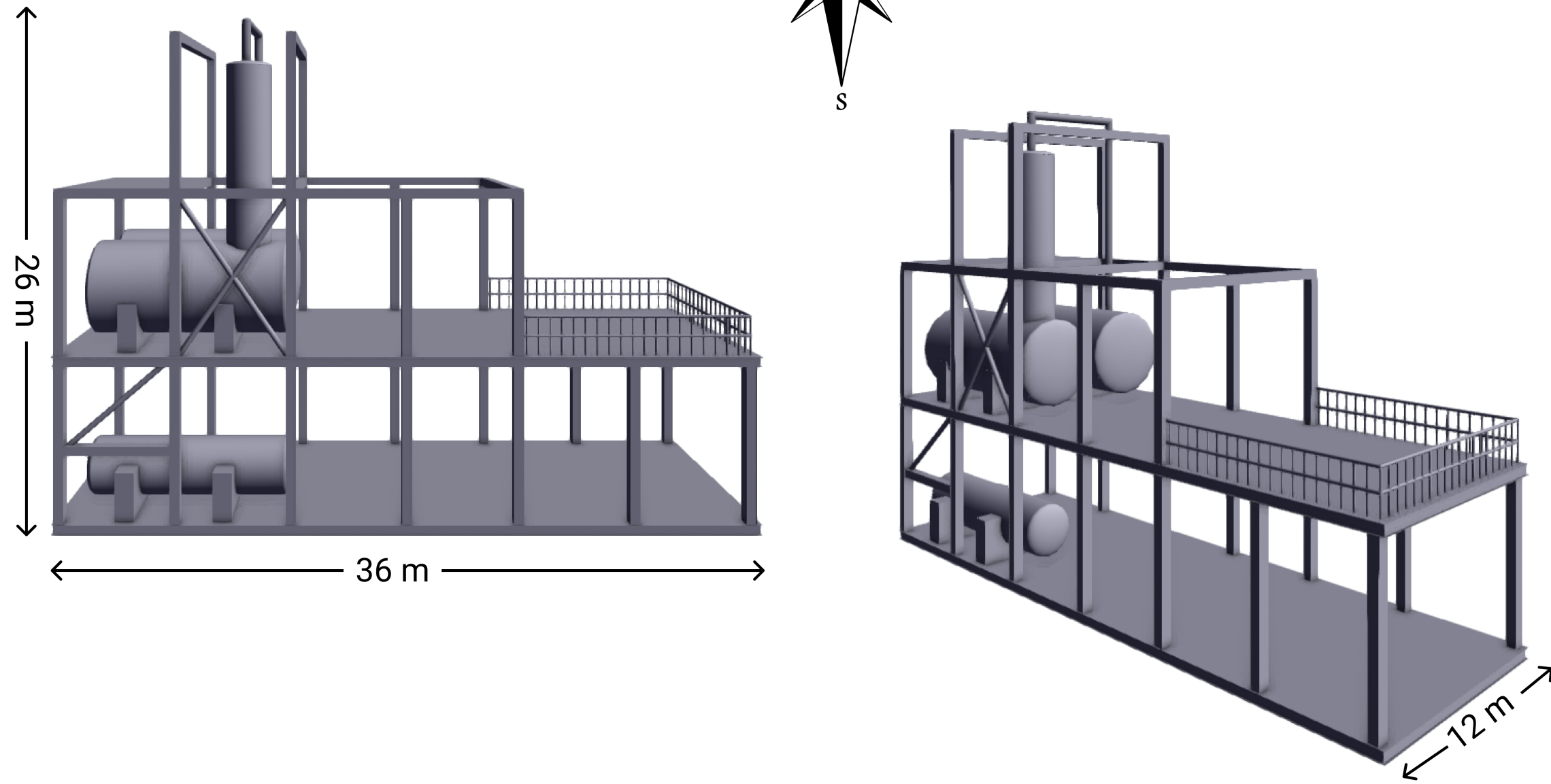
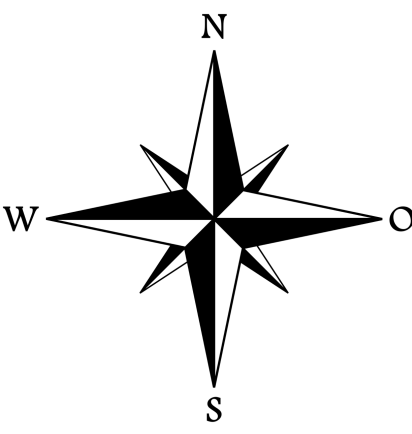
$$R = \frac{\dot{m}}{\rho Q}$$

$$\hat{V} = \frac{u^{1.5} \rho^{1.5} V_f}{\dot{m}^{1.5}}$$

Results



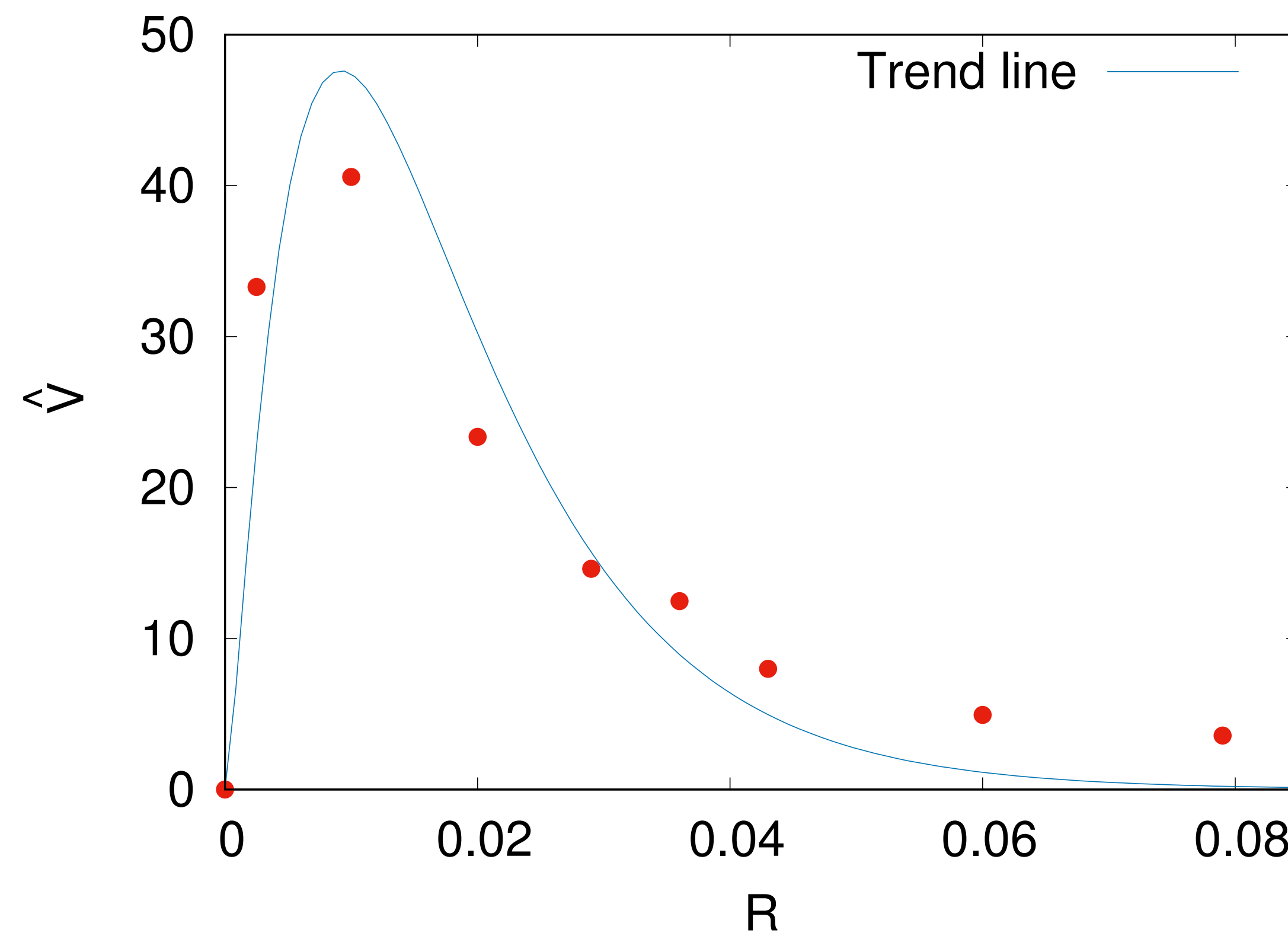
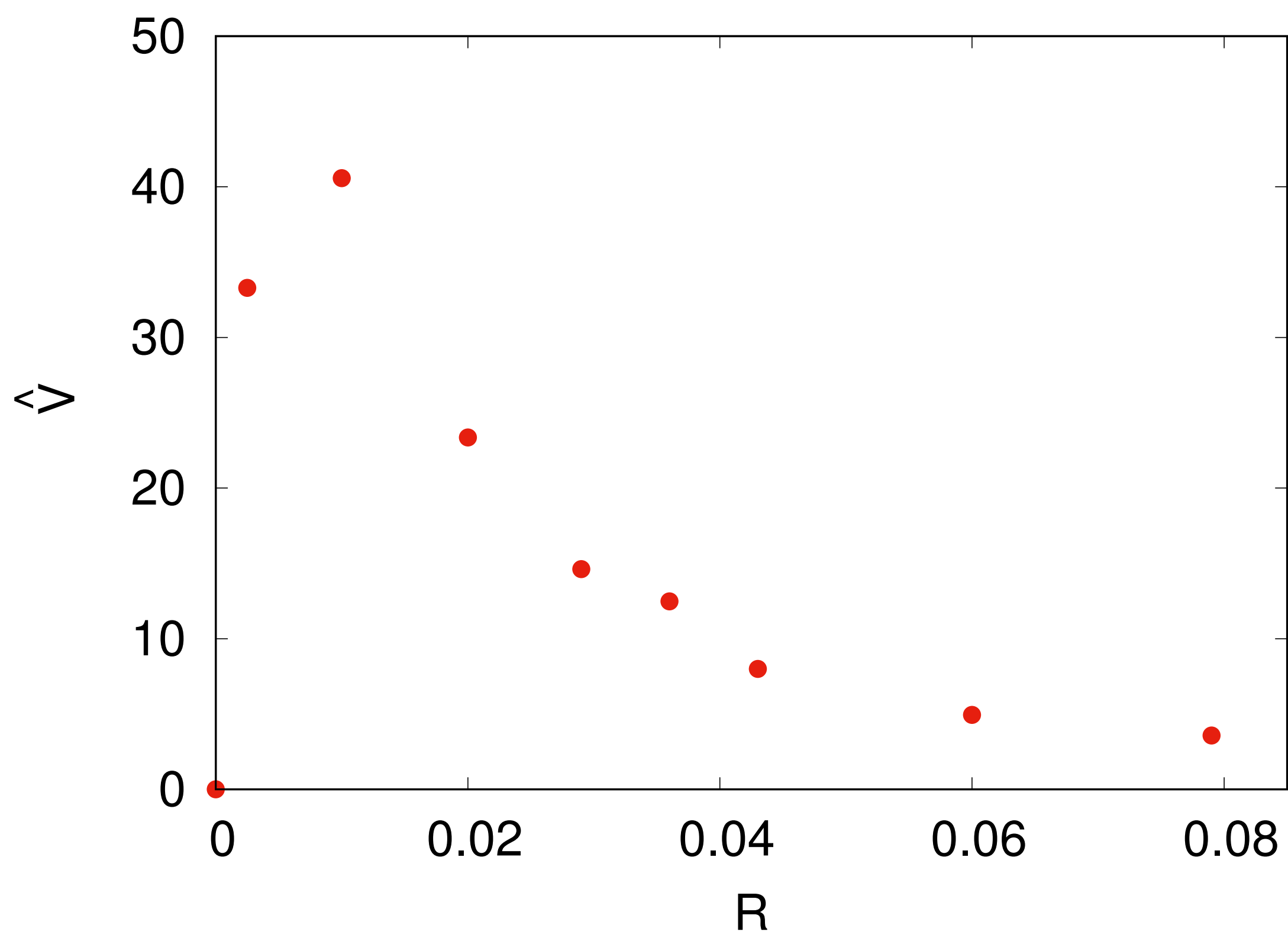
UNICAMP



- ~ 240 CFD simulations
- RANS
- K-epsilon model
- FLACS
- Neutral Pasquill stability class

Leak \ Wind	Up	Down	East	West	North	South
North	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates
South	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates
East	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates
West	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates	10 leak rates

Results



Results

Modelling

- Gas particles density is not high
- Gas particles are in constant random movement
- Gas particles do not interact with each other
- Collisions are elastic
- Particle velocities along all directions are equivalent



$$\Omega(v_x, v_y, v_z) = f(v_x)f(v_y)f(v_z)$$

$$\ln \Omega(v_x, v_y, v_z) = \ln f(v_x) + \ln f(v_y) + \ln f(v_z)$$

Differentiation for v_x leads to:

$$\left(\frac{\partial \ln \Omega(v)}{\partial v_x} \right)_{v_y, v_z} = \frac{d \ln f(v_x)}{dv_x}$$

After minor manipulation, integration leads to:

$$f(v_j) = \omega \exp\left(-\frac{\gamma v_j^2}{2}\right) \frac{\dot{m} \Delta t}{\rho}$$

Integration over the sample of velocities

$$V = \frac{\dot{m} \Delta t}{\rho} \omega \exp\left[-\frac{\gamma \left(\frac{\dot{m}}{\rho A}\right)^2}{2}\right]$$

Results

Modelling

$$V = \frac{\dot{m}\Delta t}{\rho}\omega \exp\left[-\frac{\gamma\left(\frac{\dot{m}}{\rho A}\right)^2}{2}\right]$$

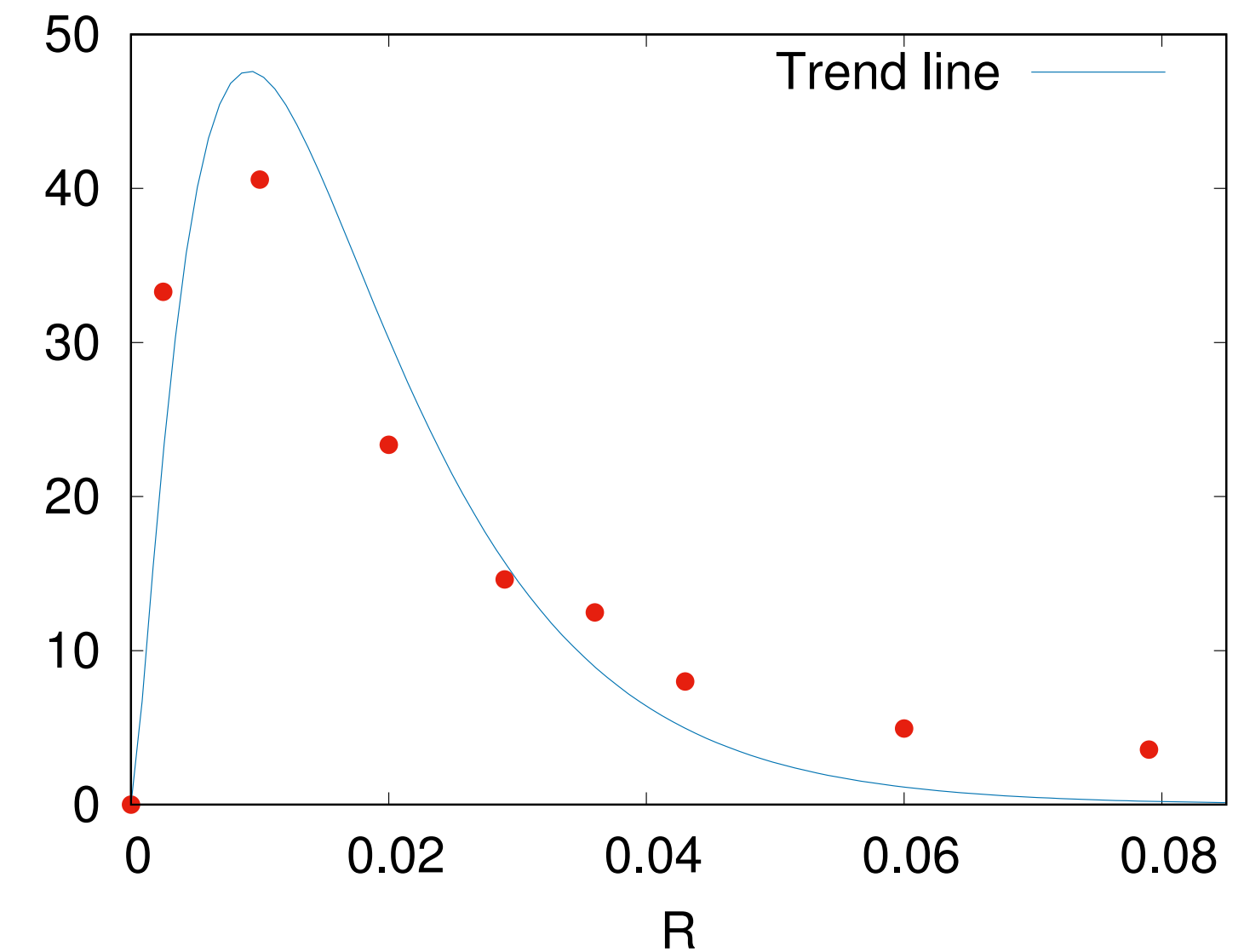


$$A = \frac{\omega\Delta T}{\rho}$$

$$B = \frac{\gamma}{2(\rho A)^2}$$

$$V = A\dot{m} \exp\left(-B\dot{m}^2\right)$$

$$\hat{V} = AR \exp\left(-BR^2\right)$$

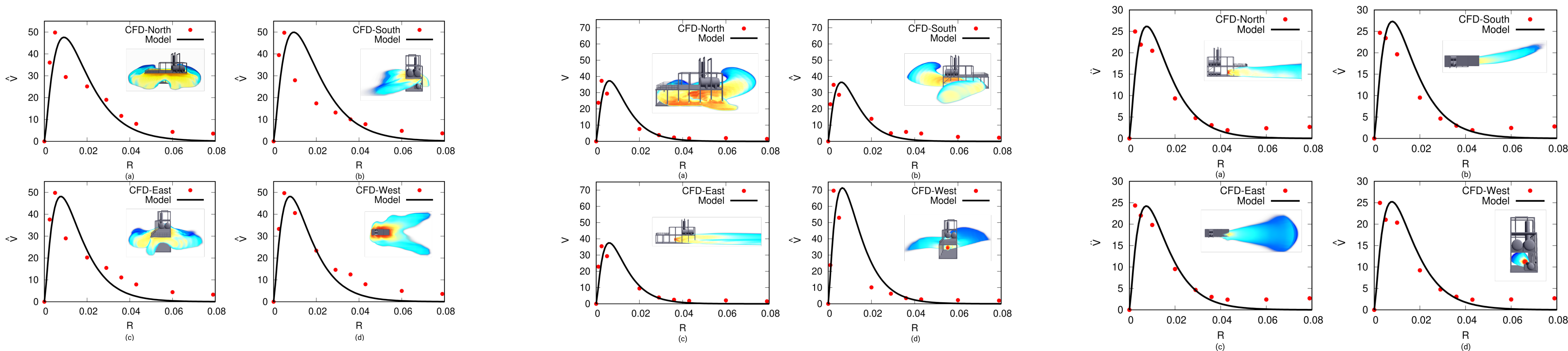


Comparison with CFD suggests the following:

$$\hat{V} = A^m R^n \exp\left(-BR^{0.8}\right)$$

where $m = n = 1.5$

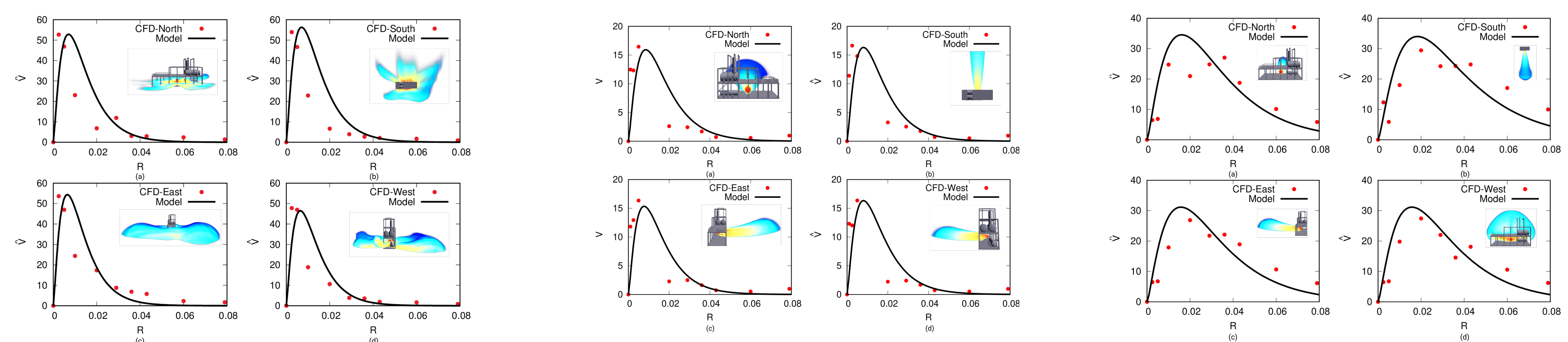
Results



Up

West

East

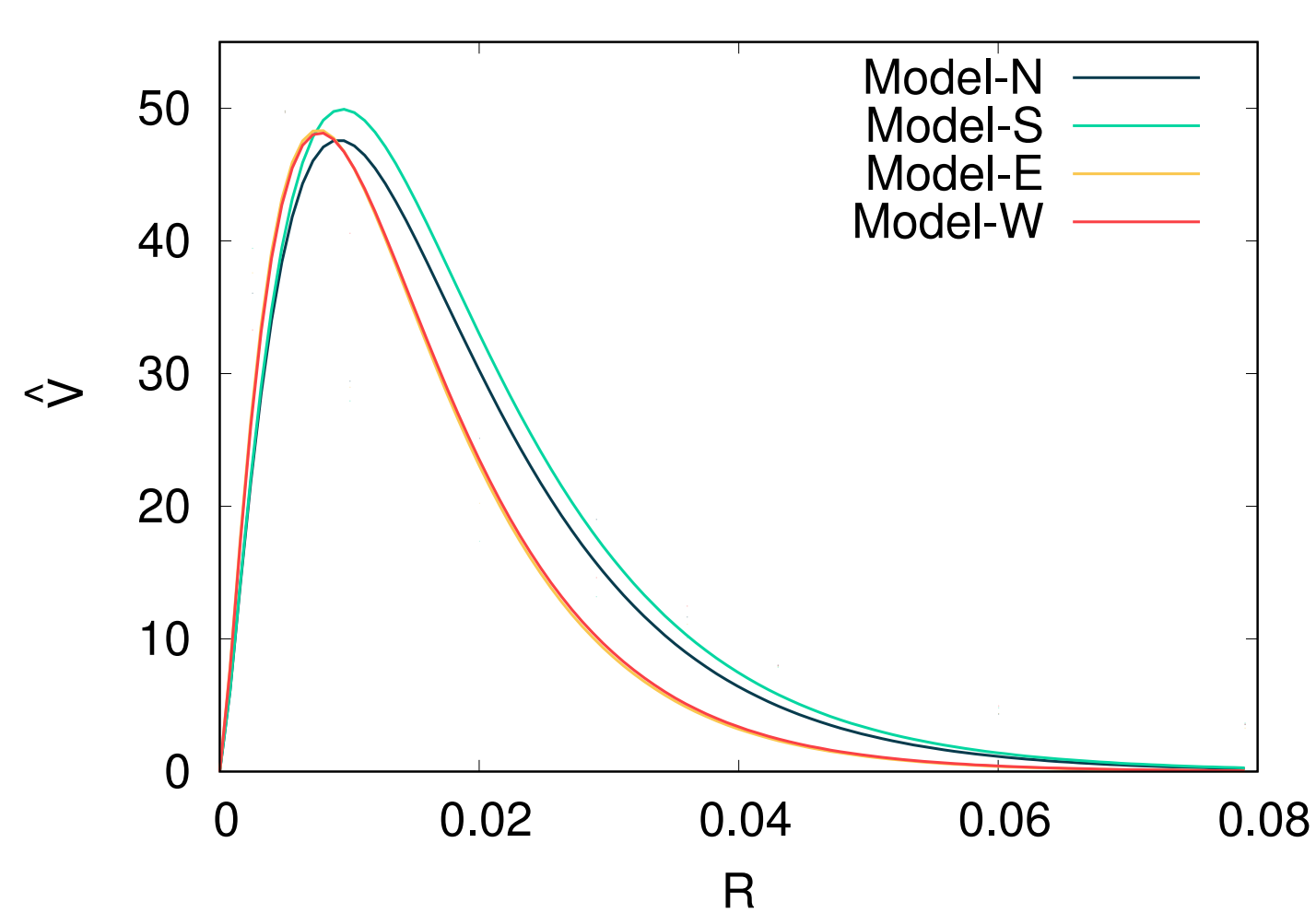


Down

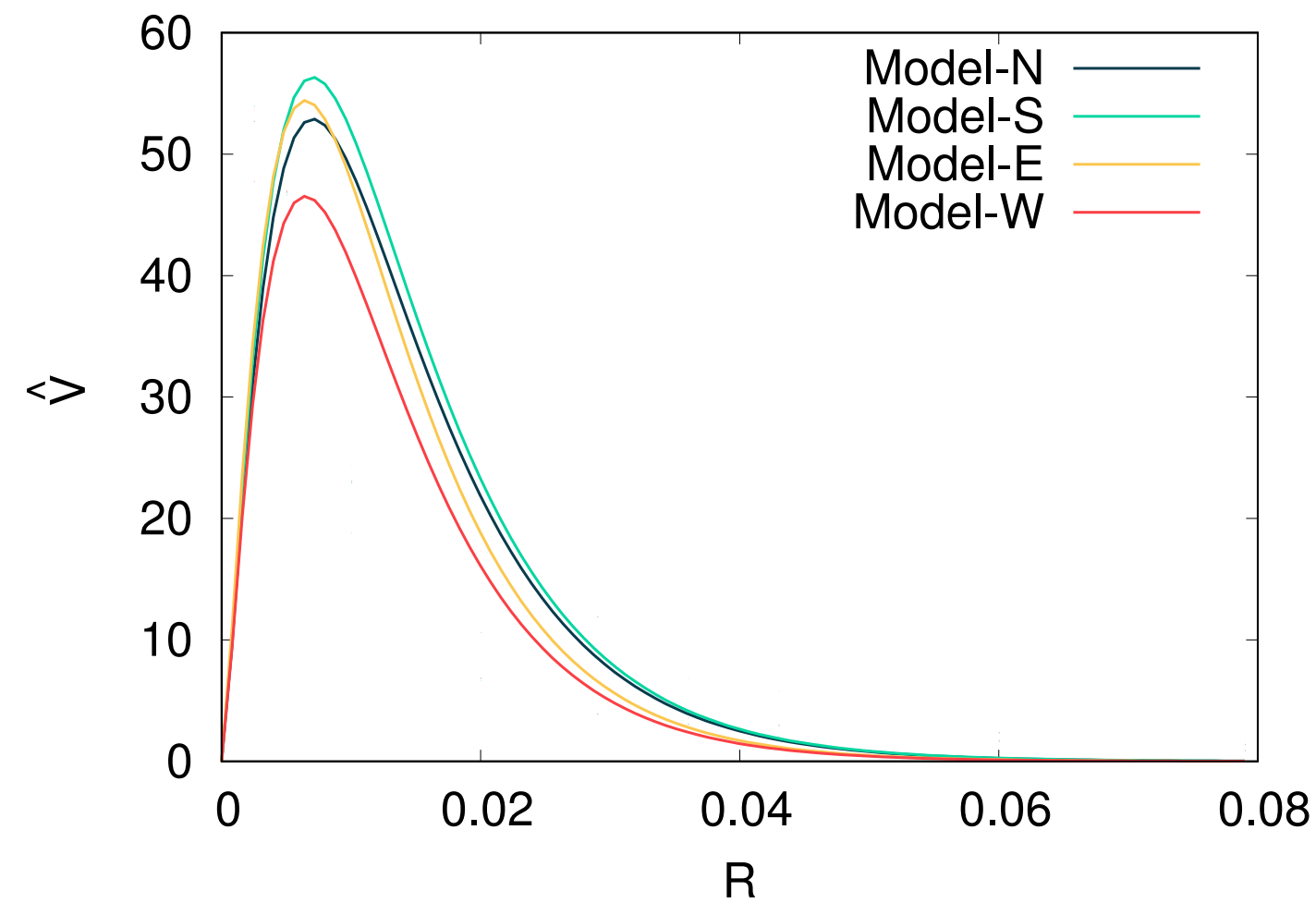
North

South

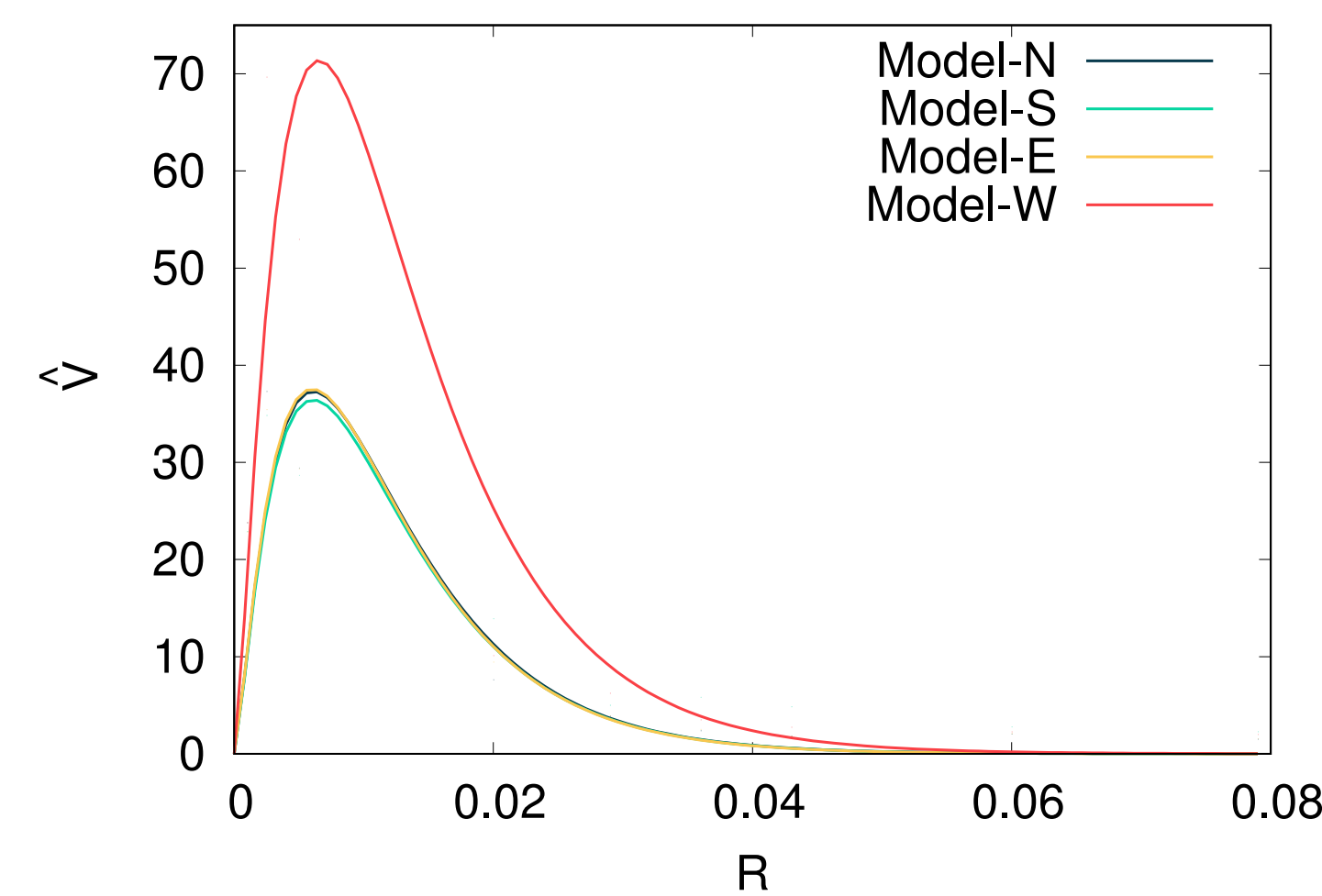
Results



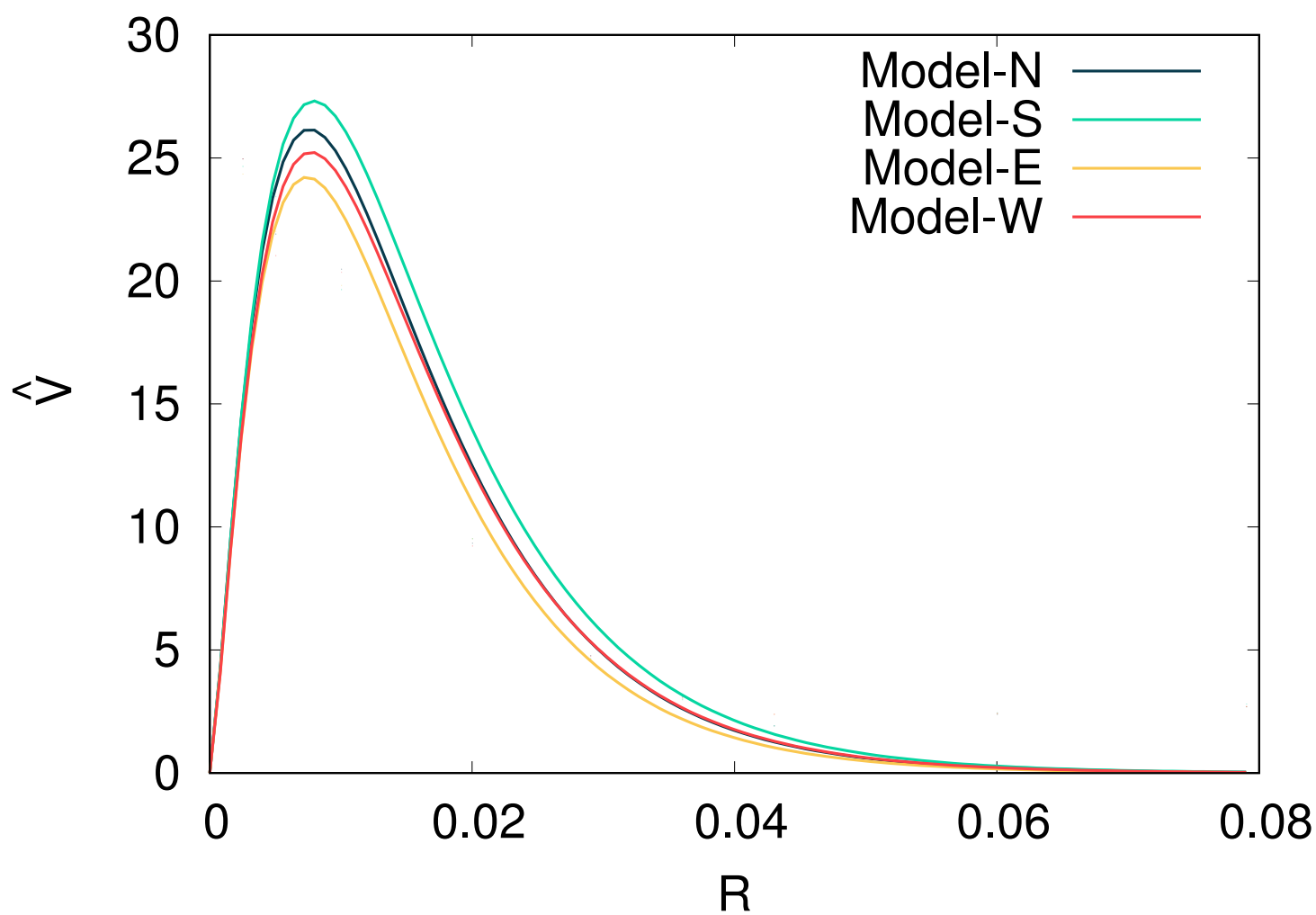
Up



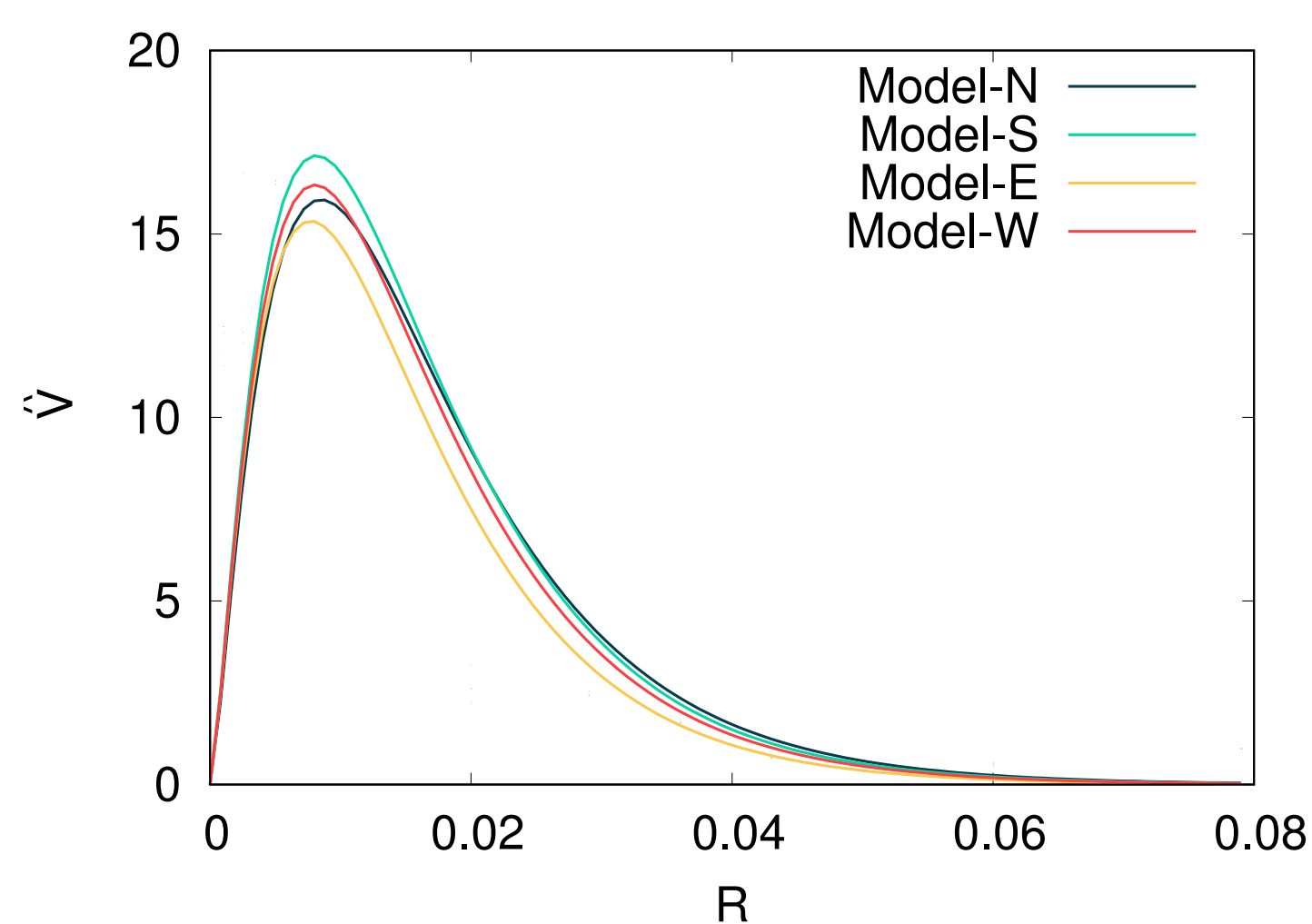
Down



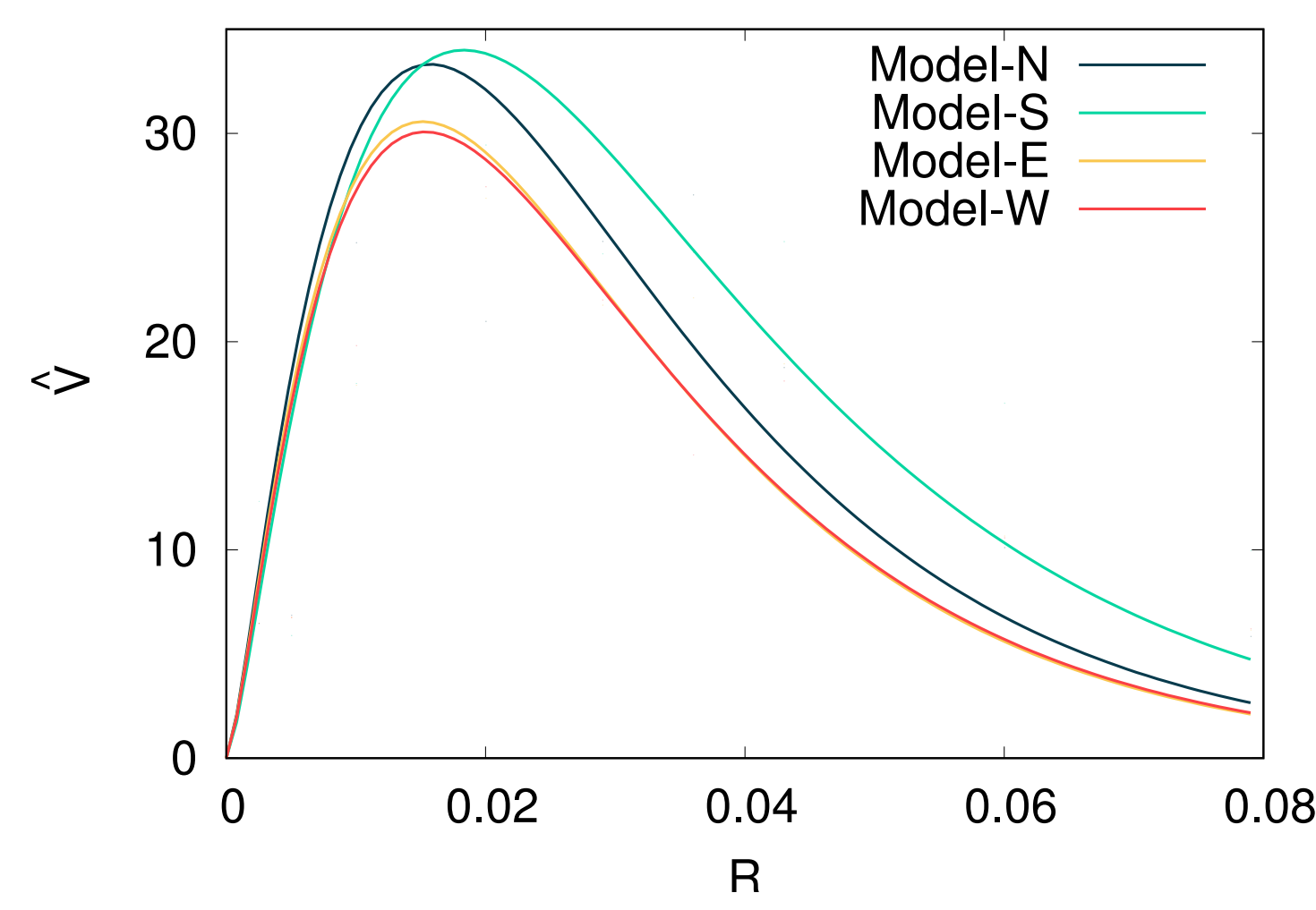
West



East

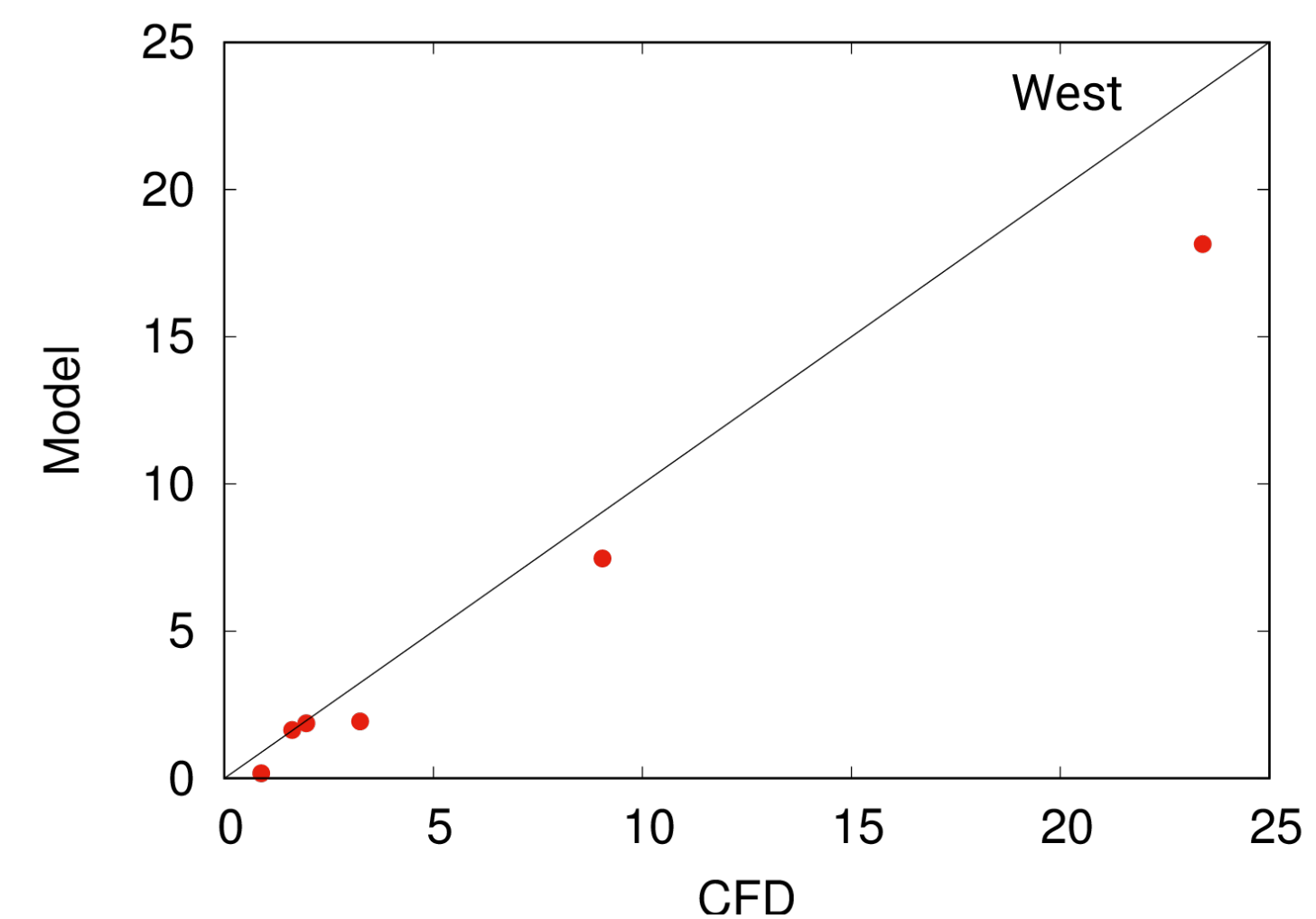
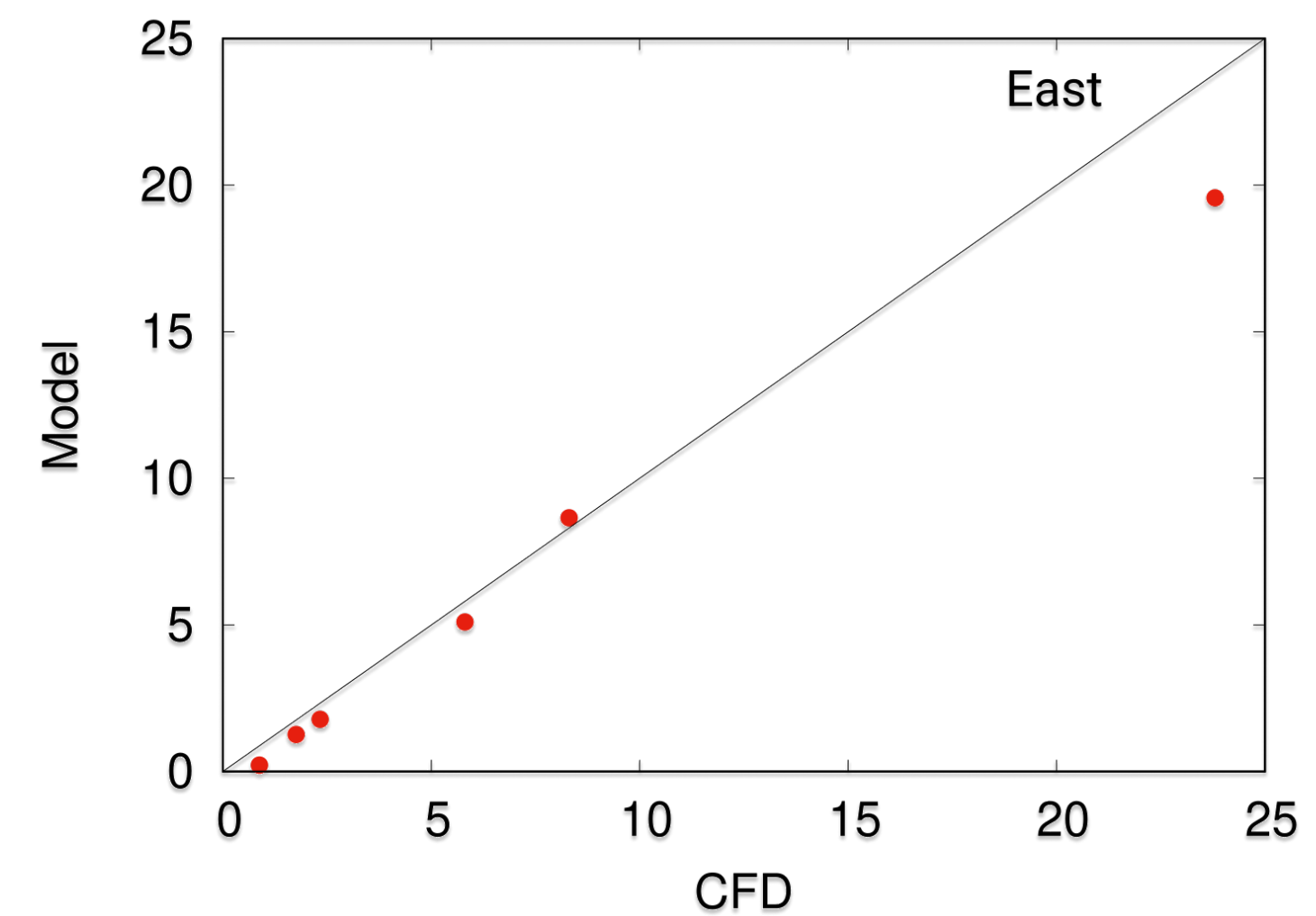
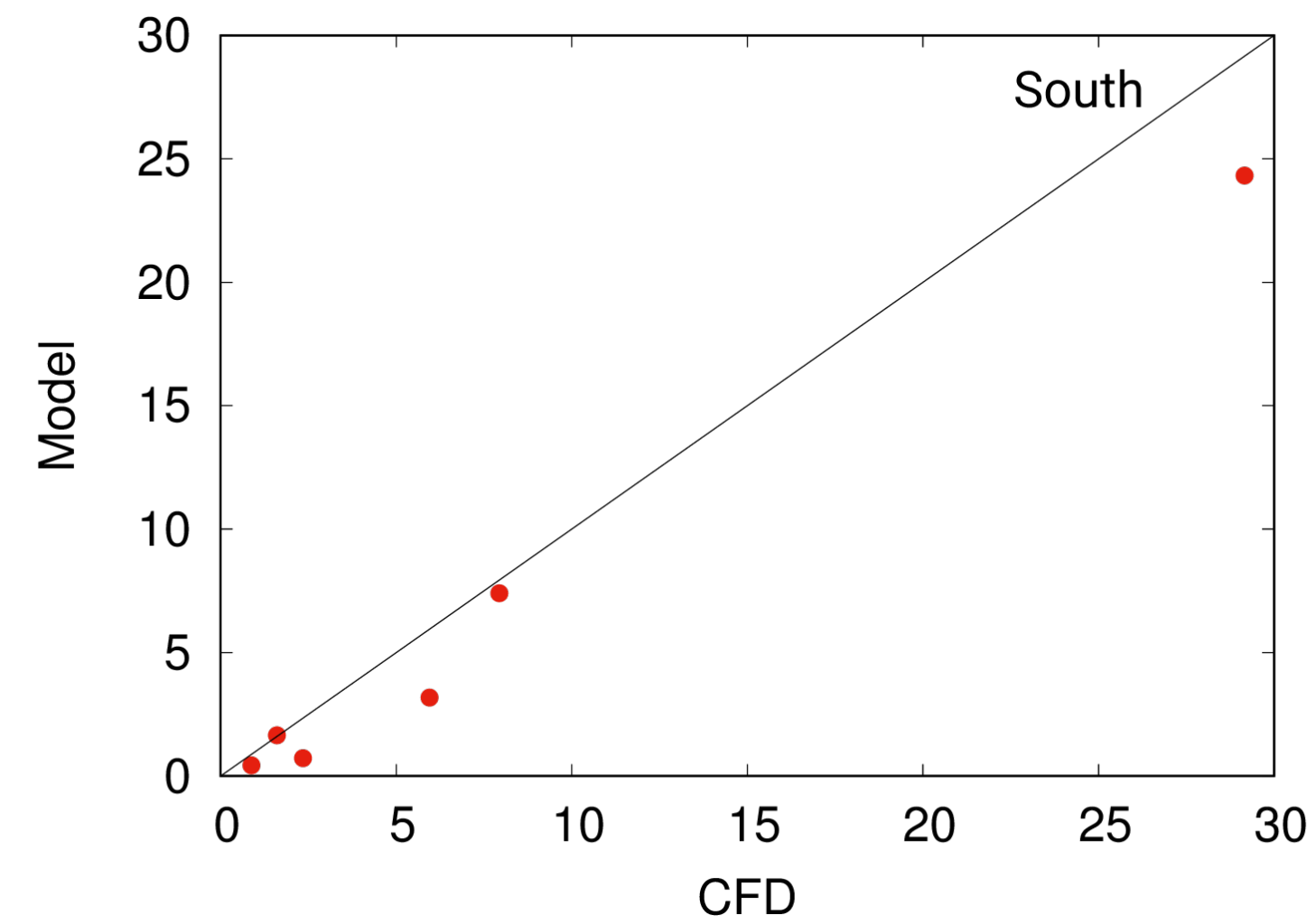
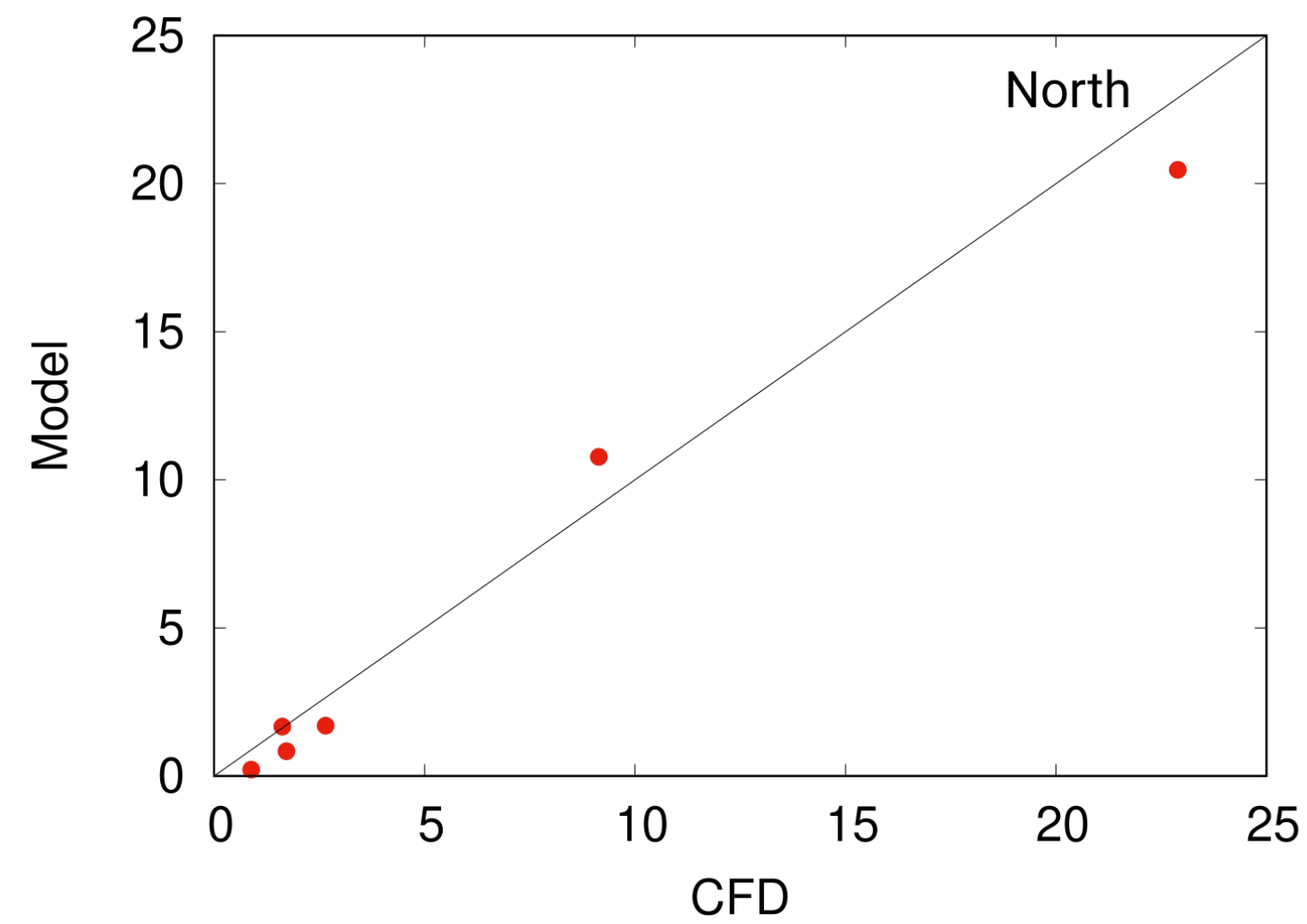


North

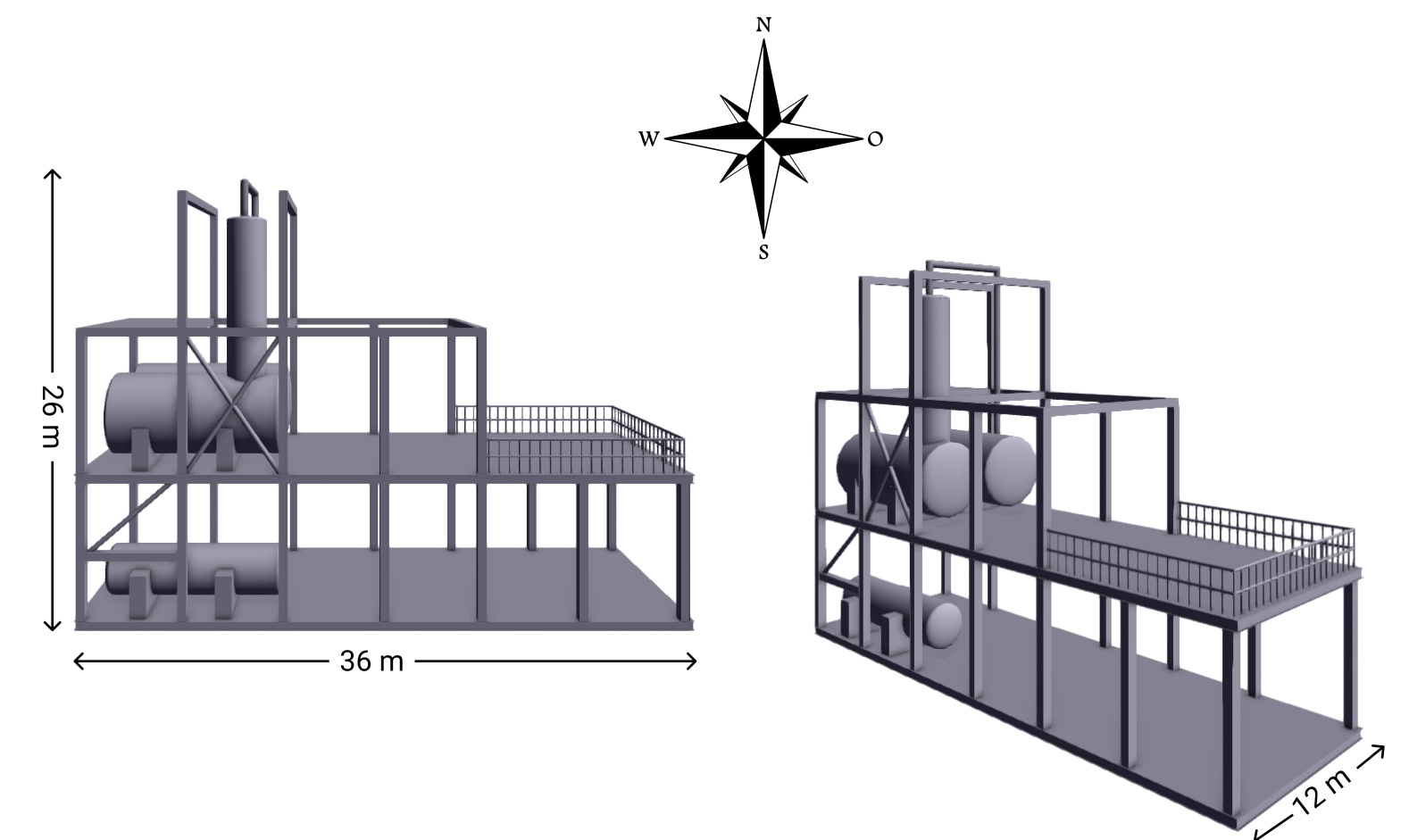


South

Results - Validation



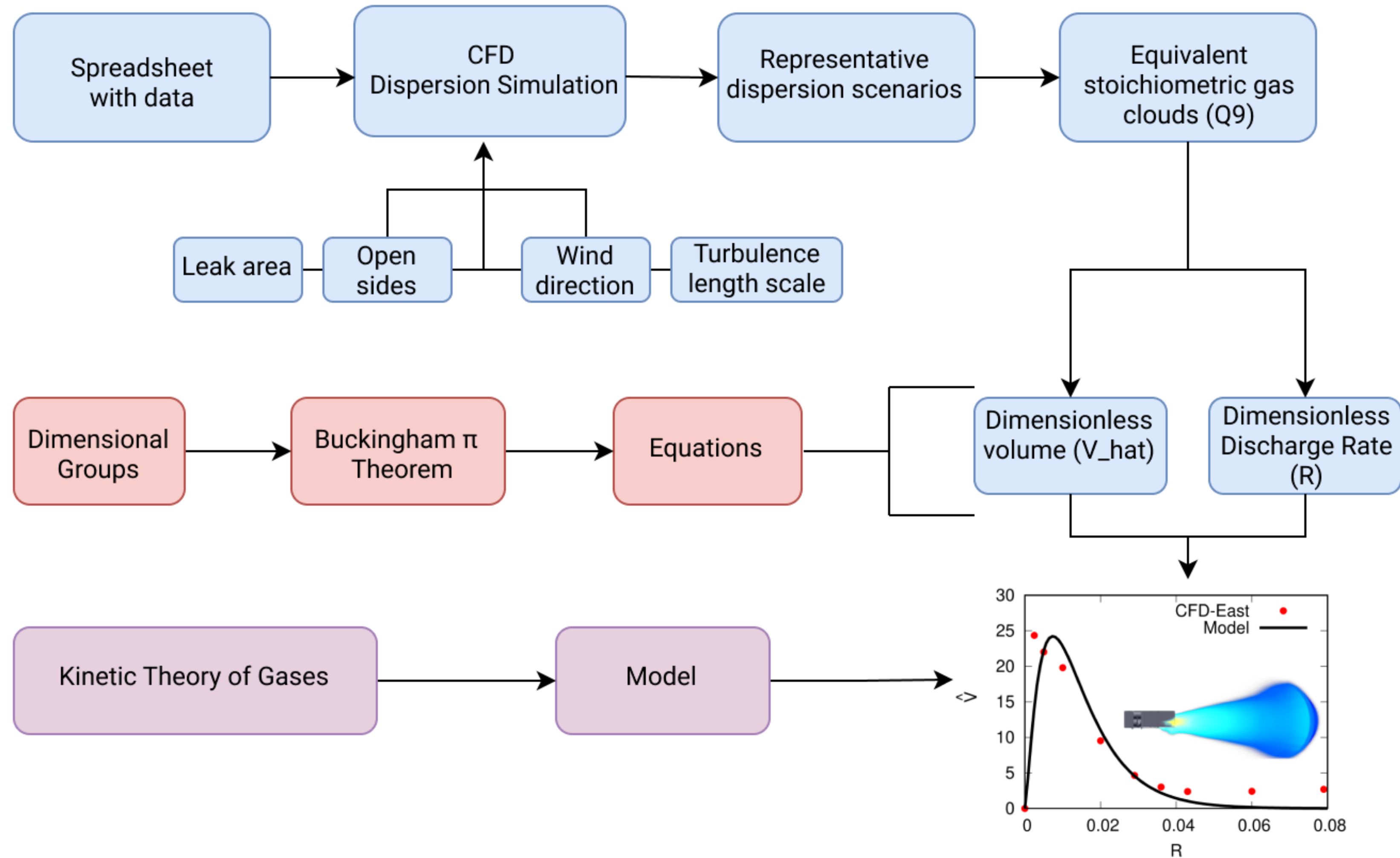
- A new set of CFD simulation was used in the validation process
- Overall good agreement was observed



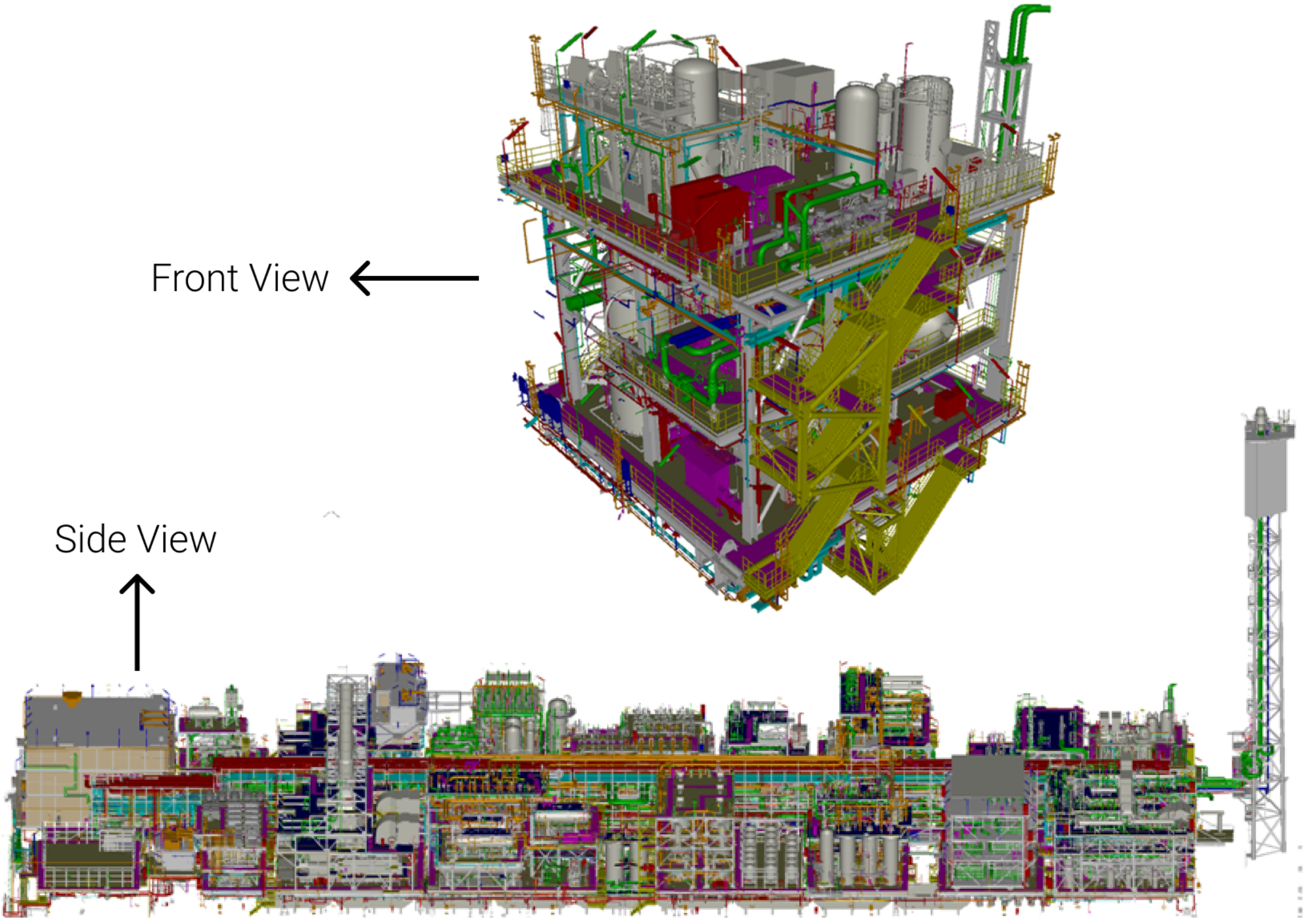
Results



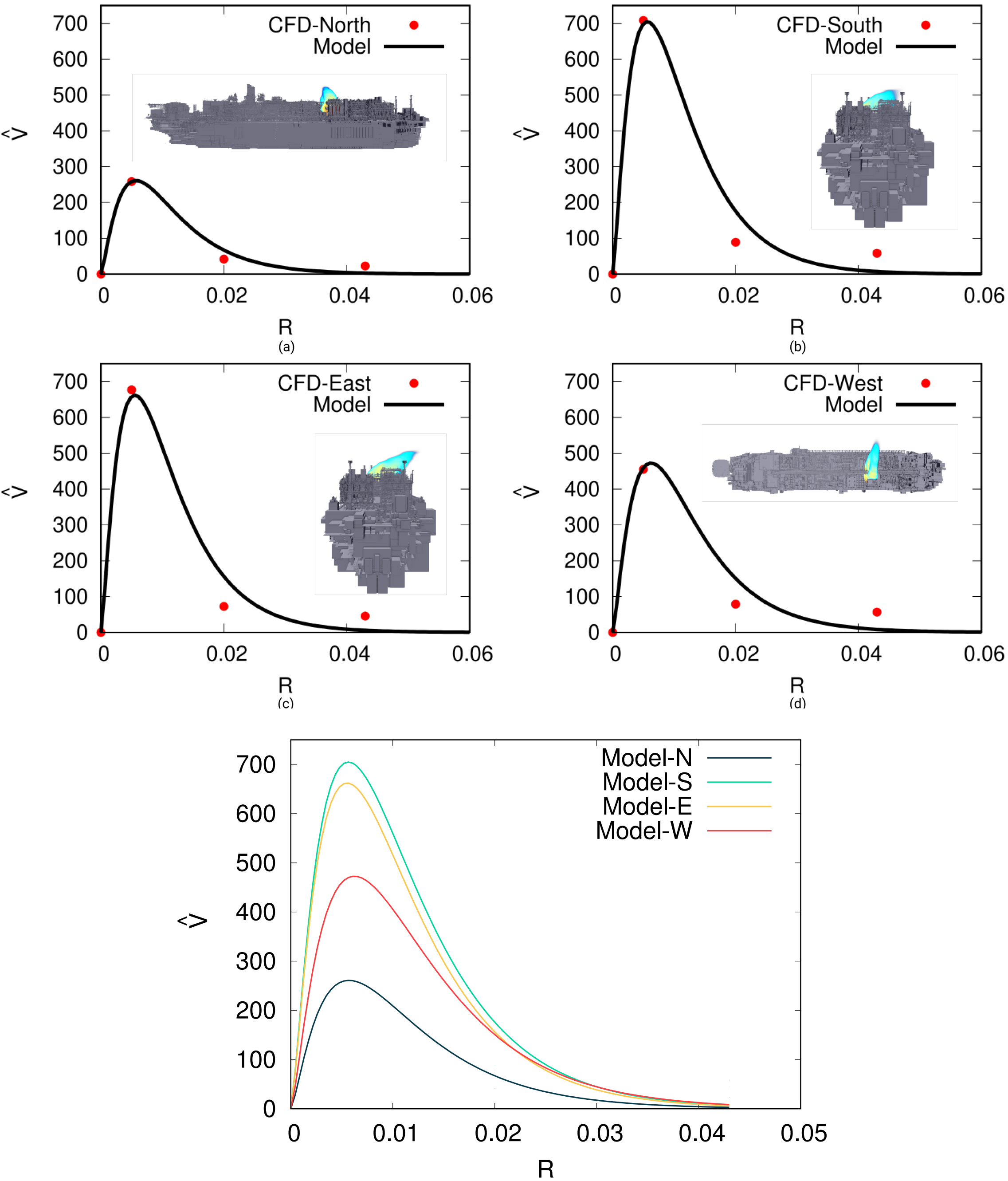
UNICAMP



Results - Engineering case



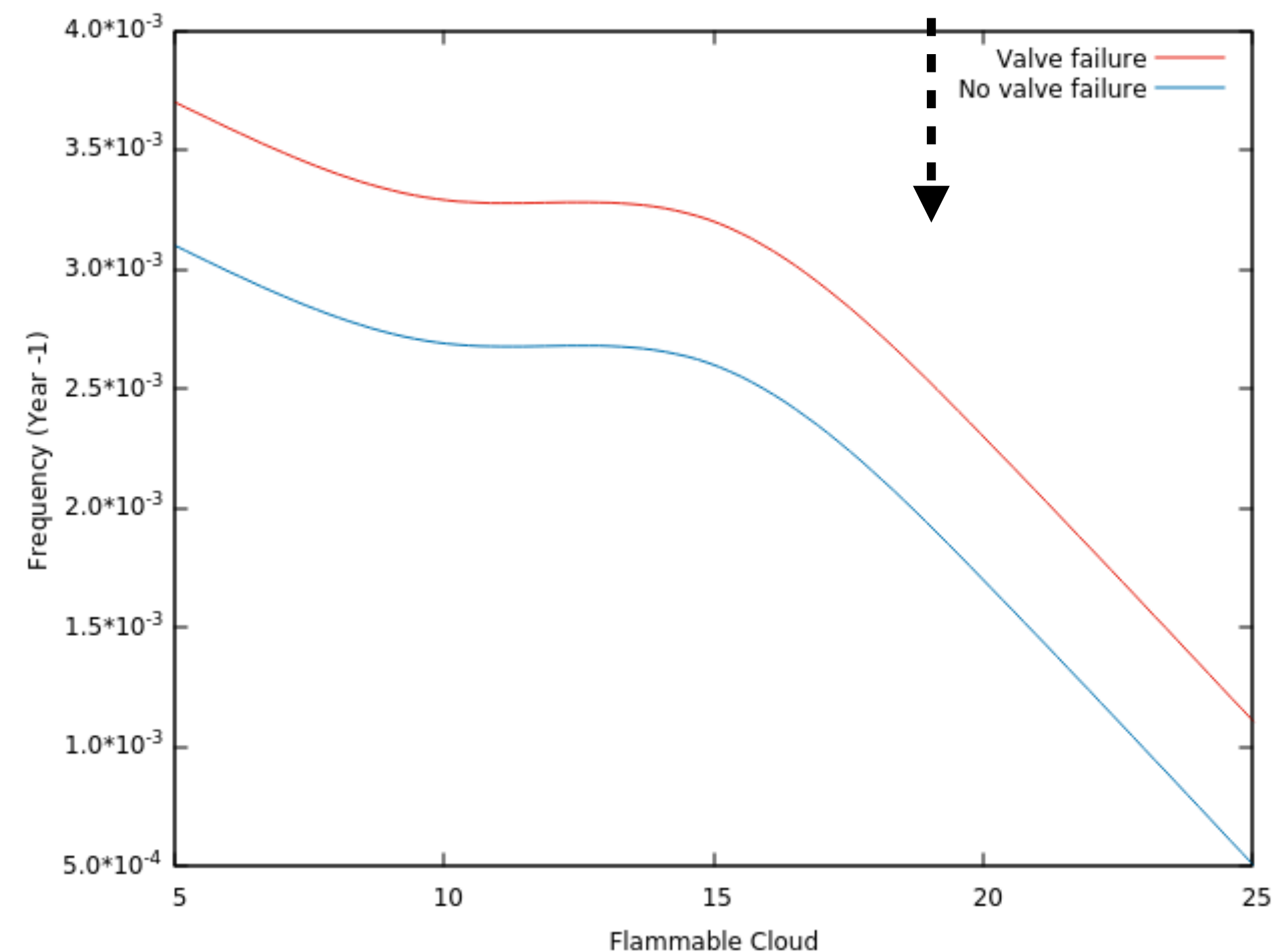
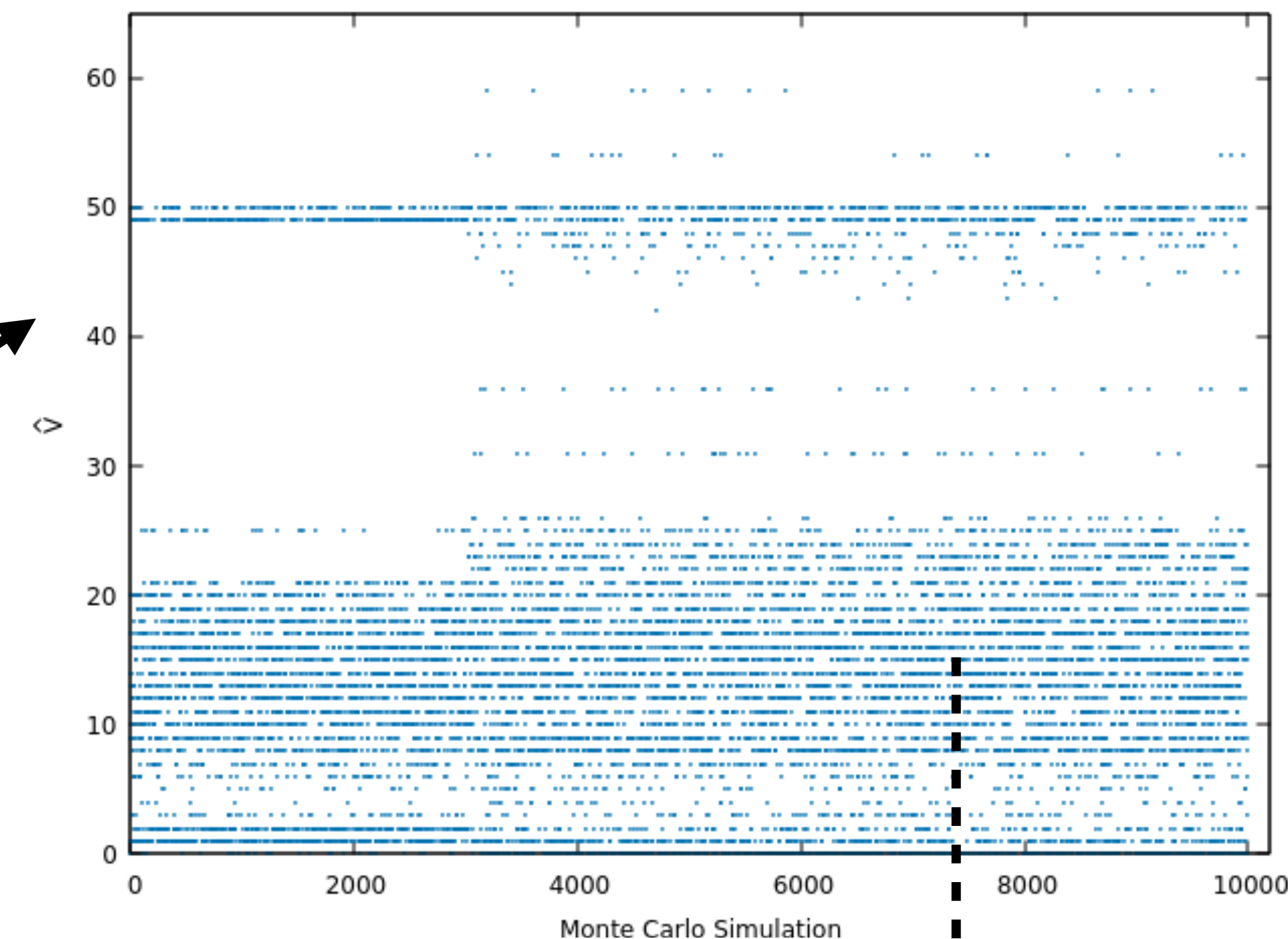
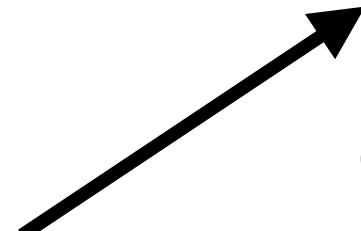
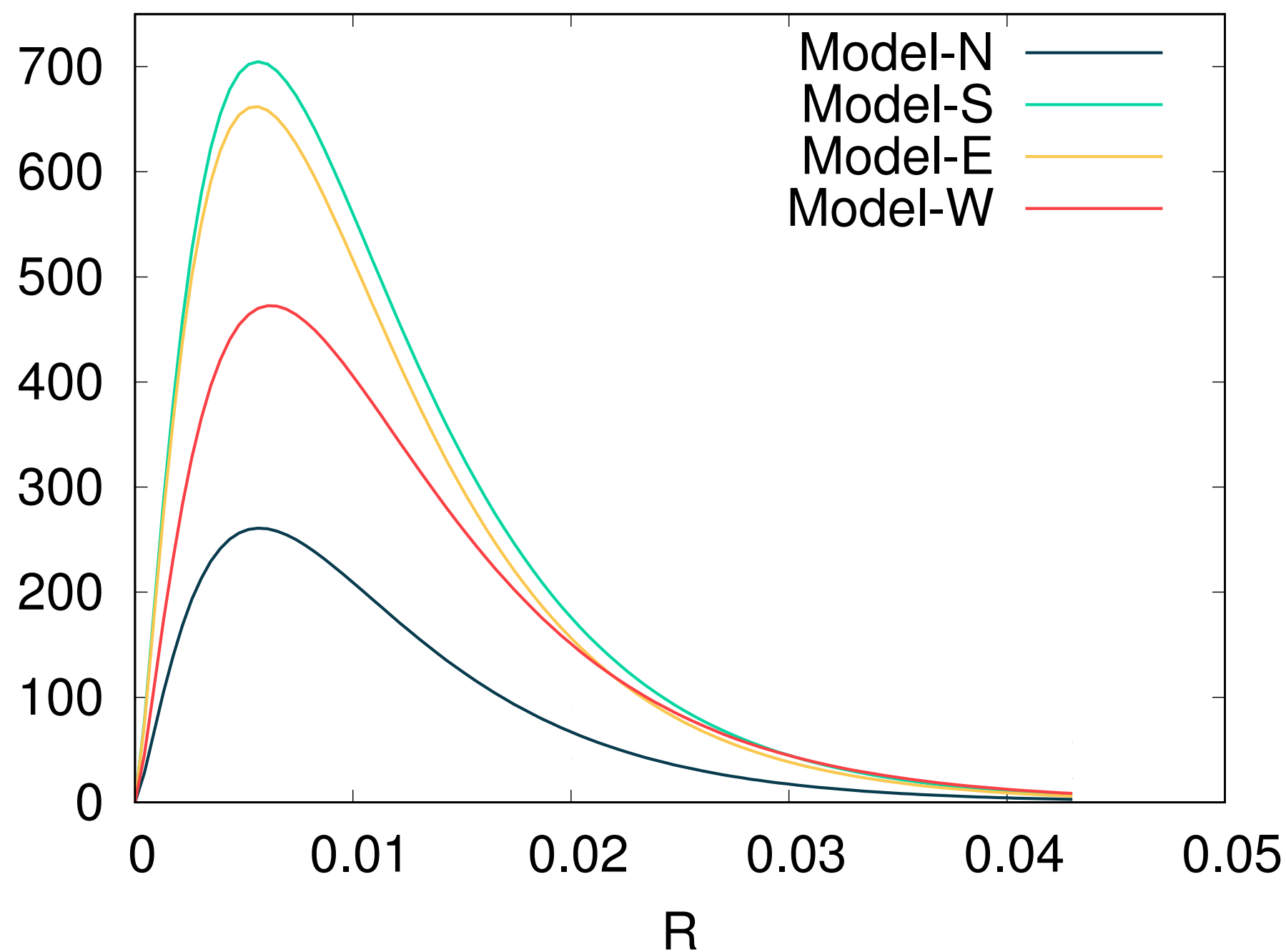
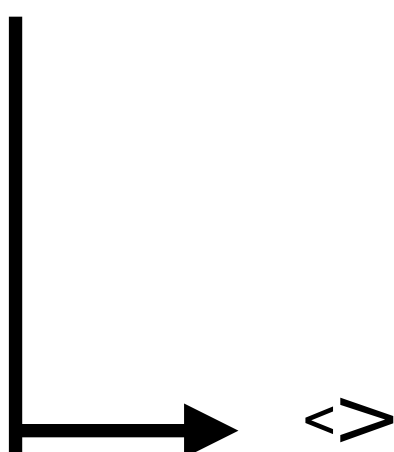
Petrobras - FPSO



Results - Applications

$$R = \frac{\dot{m}}{\rho Q \frac{u}{u_{ref}}}$$

$$\hat{V} = \frac{u^{1.5} \rho^{1.5} V_f}{\dot{m}^{1.5}}$$



Closing remarks



Simulador Monte Carlo Petrobras

Taxa de descargaDados do ventoDados dos ModelosCalcula Monte Carlo

Dados do Modelo de Ventilação

Direção Norte

A: 410.0B: 125.0VA (m³/s): 50.0Uref (m/s): 6.0

Direção Nordeste

A: 410.0B: 135.0VA (m³/s): 50.0Uref (m/s): 6.0

Direção Leste

A: 320.0B: 100.0VA (m³/s): 50.0Uref (m/s): 6.0

Direção Sudeste

A: 350.0B: 120.0VA (m³/s): 50.0Uref (m/s): 6.0

Direção Noroeste

A: 410.0B: 120.0VA (m³/s): 50.0Uref (m/s): 6.0

Direção Oeste

A: 400.0B: 110.0VA (m³/s): 50.0Uref (m/s): 6.0

Direção Sudoeste

A: 425.0B: 115.0VA (m³/s): 50.0Uref (m/s): 6.0

Direção Sul

A: 450.0B: 120.0VA (m³/s): 50.0Uref (m/s): 6.0

Dados do Modelo de Explosão

Po (bar): 500.0n: 1.5

$P = P_0 G^n$

Simulador Monte Carlo Petrobras

Taxa de descargaDados do ventoDados dos ModelosCalcula Monte Carlo

Probabilidades da Direção do Vento

Norte: 0,21572733235Sul: 0,09166288241Leste: 0,14137948433Oeste: 0,03014783793Nordeste: 0,33236624787Noroeste: 0,02415190810Sudeste: 0,09844089005Sudoeste: 0,06612341692

Velocidade (m/s)	Freq. ocorrência (0-1)
0.0-1.0	0,016600232...
1.0-2.0	0,031140151...
2.0-3.0	0,059833156...
3.0-4.0	0,083135711...
4.0-5.0	0,113191045...
5.0-6.0	0,111980086...
6.0-7.0	0,126183628...
7.0-8.0	0,109541349...
8.0-9.0	0,104377953...
9.0-10.0	0,074465580...

	337.5-022.5	022.5-067.5	067.5
0.0-1.0	264	291	2
1.0-2.0	484	630	6
2.0-3.0	927	1440	14
3.0-4.0	1223	2336	21
4.0-5.0	1924	3582	28
5.0-6.0	2065	4035	25
6.0-7.0	2740	5105	24

Dados do vento

23.0-24.018.0-19.013.0-14.08.0-9.03.0-4.0

22.0-23.017.0-18.012.0-13.07.0-8.02.0-3.0

21.0-22.016.0-17.011.0-12.06.0-7.01.0-2.0

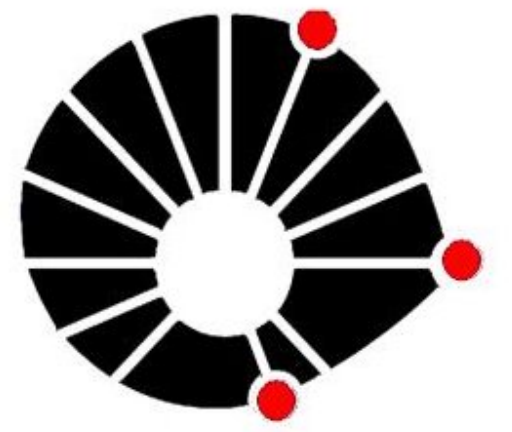
20.0-21.015.0-16.010.0-11.05.0-6.00.0-1.0

19.0-20.014.0-15.09.0-10.04.0-5.0

Carregar dados de vento

McPeas - Monte Carlo Probabilistic Explosion Analysis Simulator

Acknowledgments



UNICAMP



PETROBRAS



CAPES



prh
Programa de
Recursos Humanos
da ANP



anp
Agência Nacional
do Petróleo,
Gás Natural e Biocombustíveis

