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

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- MSc. Coppe - UFRJ
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- DnV - Det Norske Veritas
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- 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

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- Methodology
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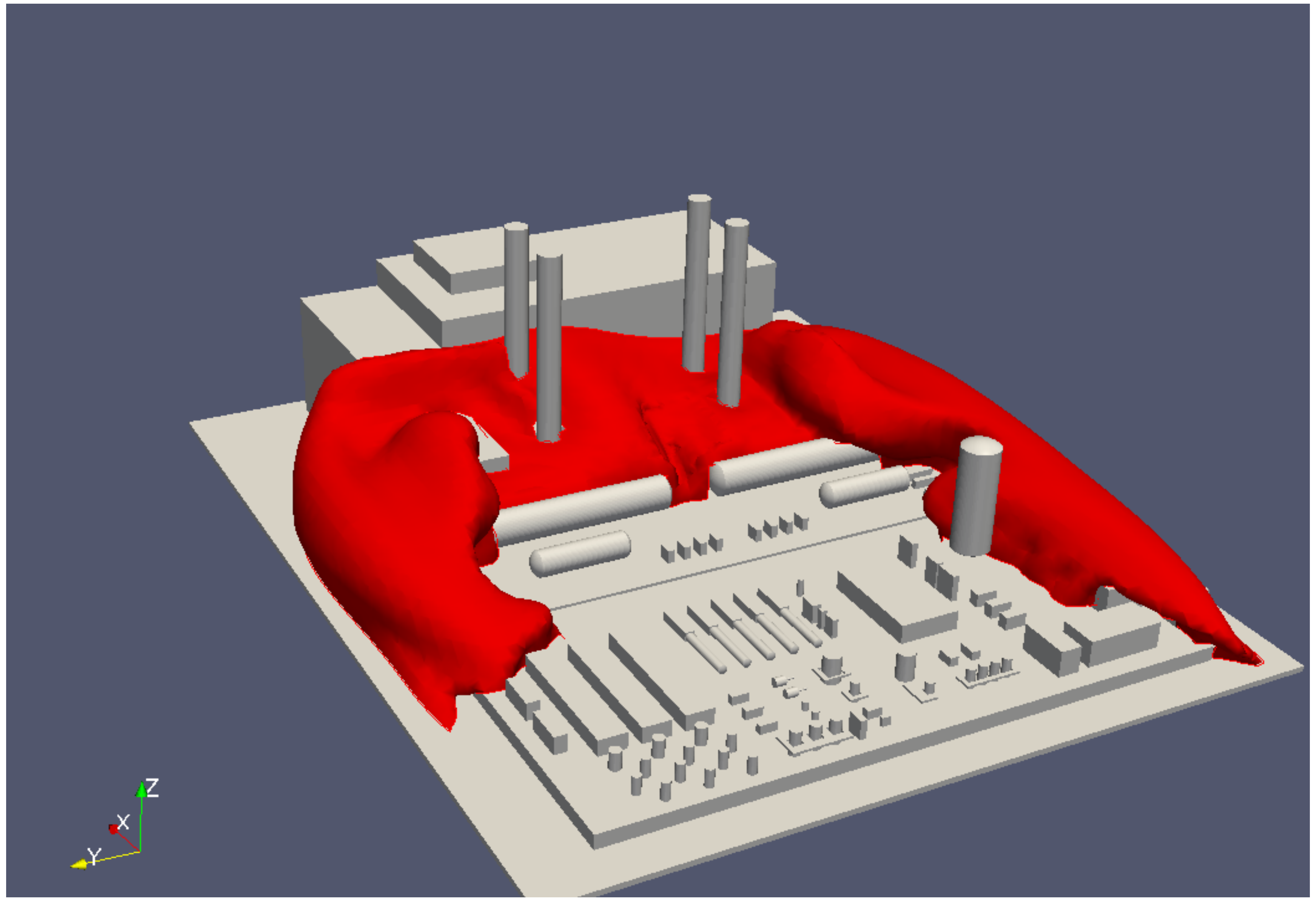
Introduction

Flammable cloud volume depends on:

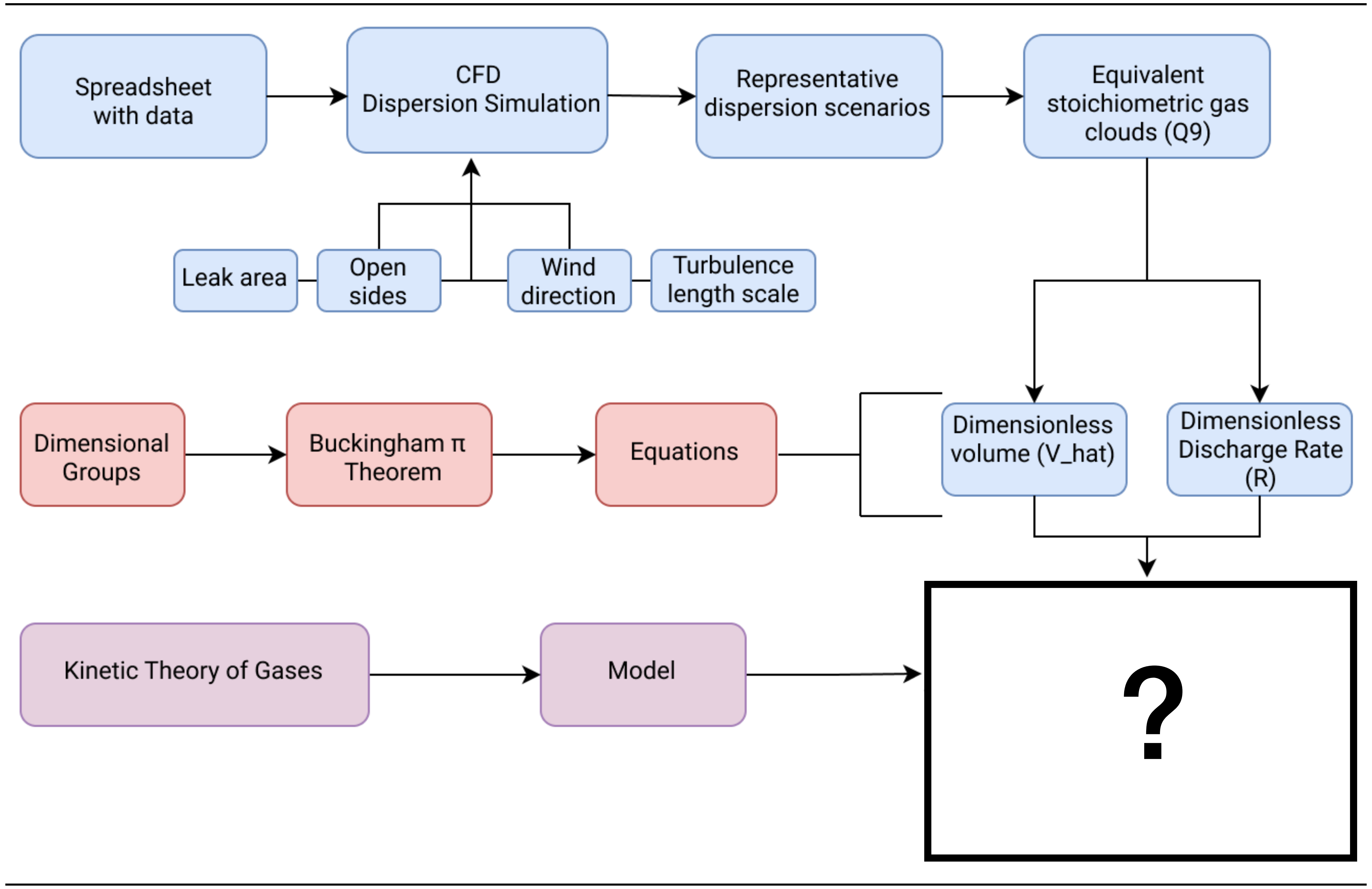
- Material released
- Wind speed
- Wind direction
- Leak rate
- Geometry



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

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

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

↓

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

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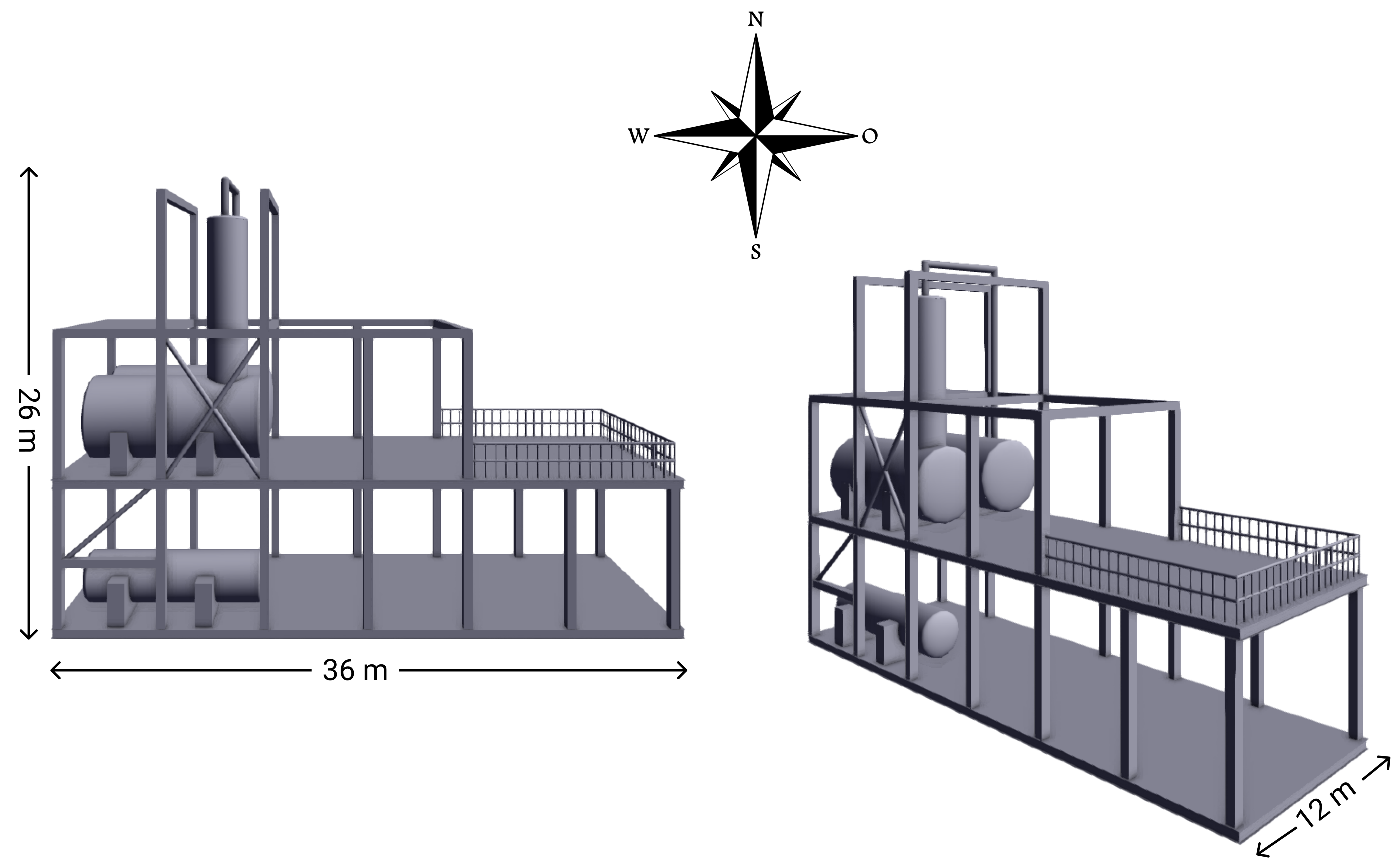
Is there any relation between the non-dimensional leak rate and the non-dimensional cloud size ?

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

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

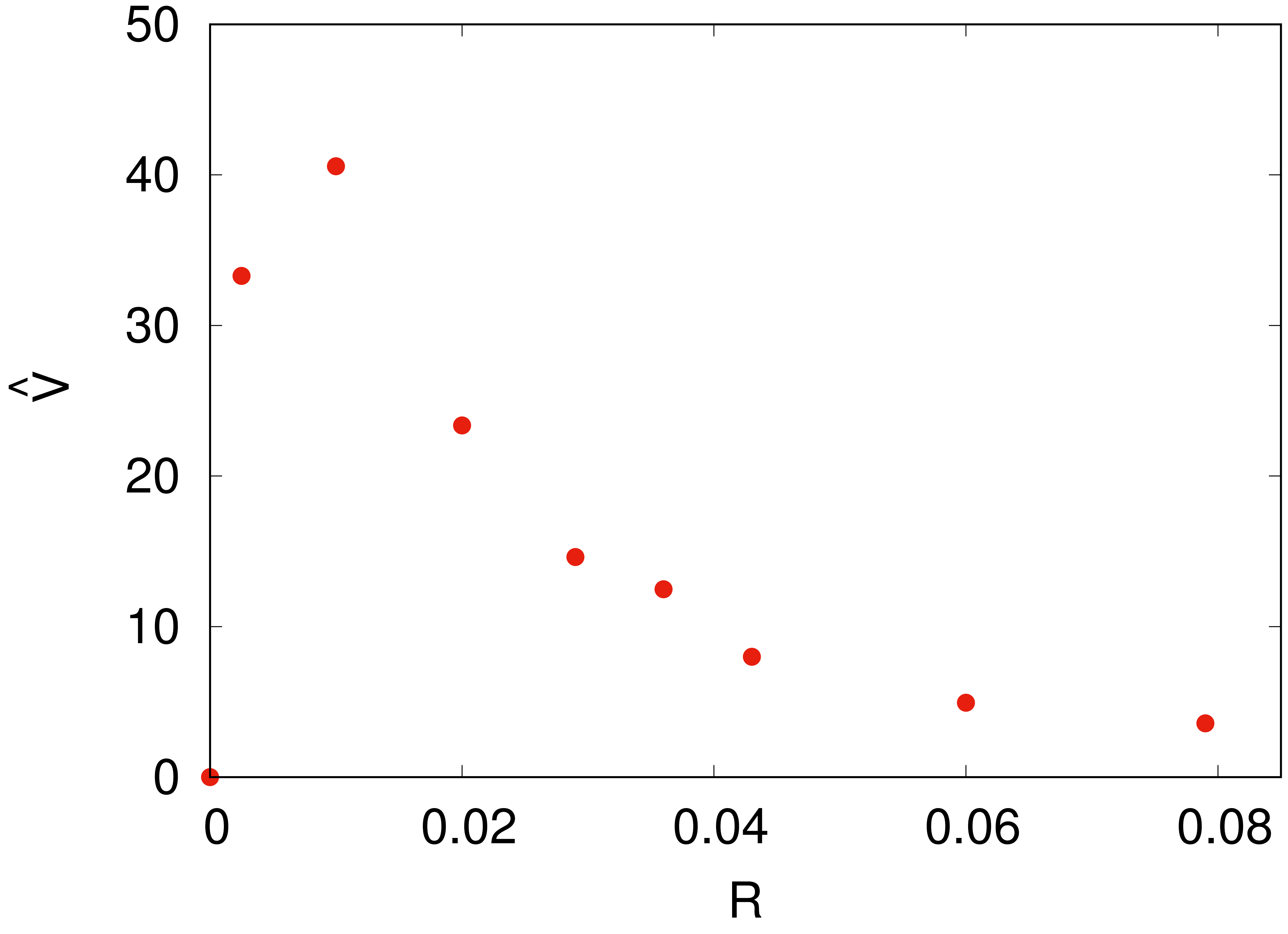
Results



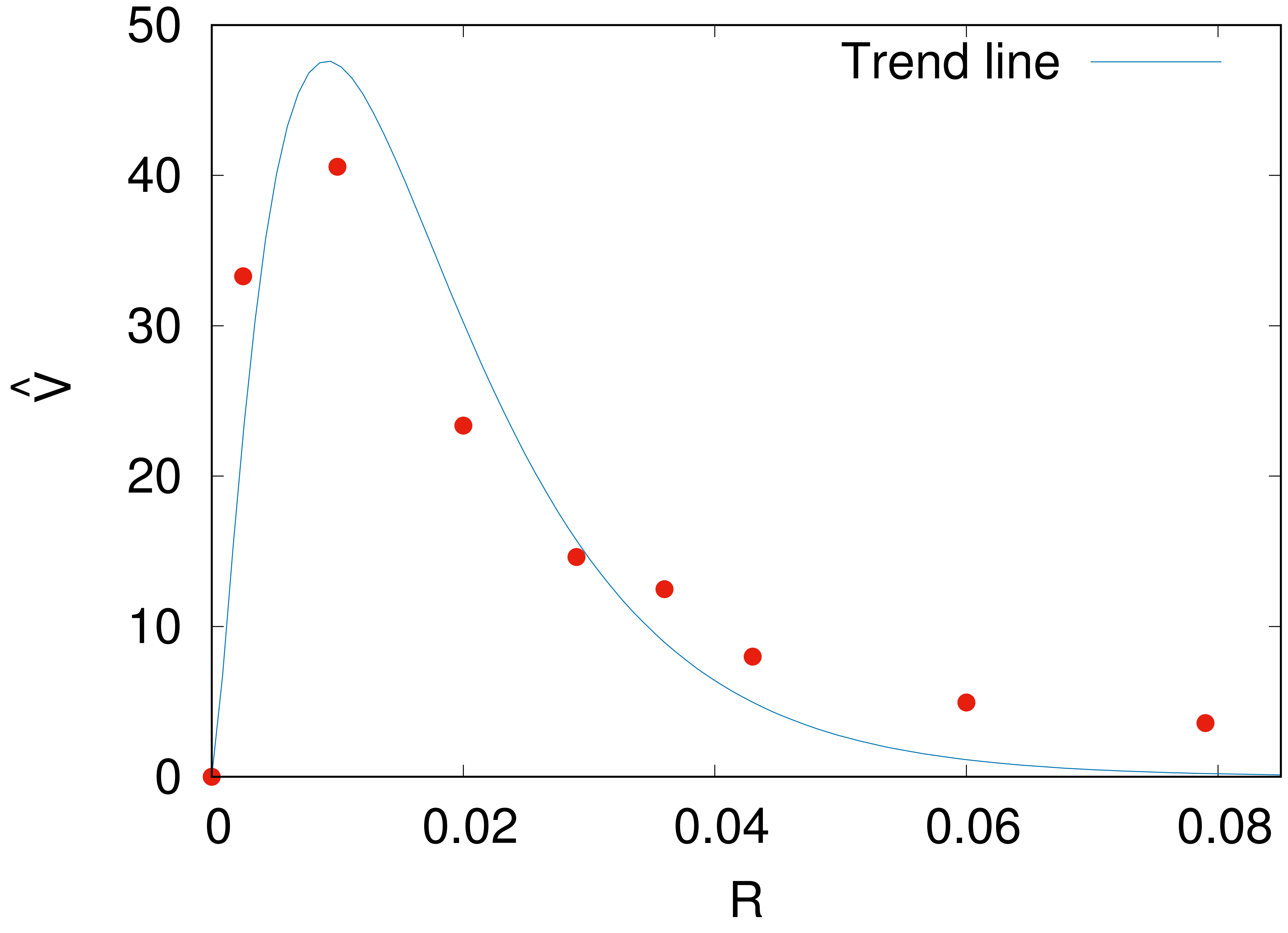
- ~ 240 CFD simulations
- RANS
- K-epsilon model
- FLACS
- Neutral Pasquill stability class

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



50
40
30
20
10
0
<V>
0
0.02
0.04
0.06
0.08
R



50
40
30
20
10
0
<V>
Trend line
0
0.02
0.04
0.06
0.08
R

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:

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

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

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

Araújo P., Vianna S.S.V. A mathematical response curve for probabilistic explosion analysis. JLPI. Volume 78. 2022, 104804

Results

Modelling

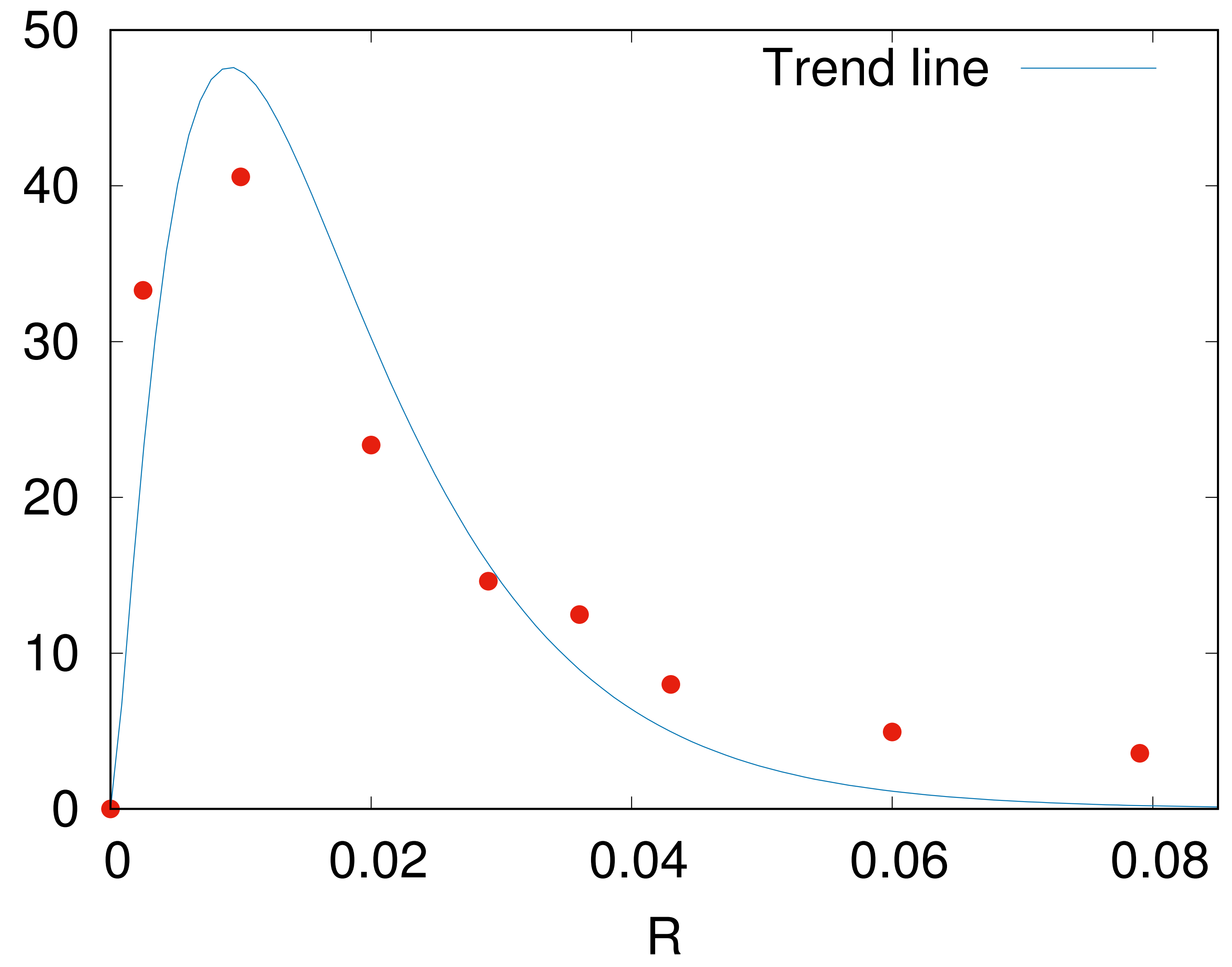
$$V = \frac{\dot{m}\Delta t}{\rho}\omega \exp\left[-\frac{\gamma\left(\frac{\dot{m}}{\rho A}\right)^2}{2}\right]$$

$$A = \frac{\omega \Delta T}{\rho} \qquad B = \frac{\gamma}{2(\rho A)^2}$$

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

<>

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

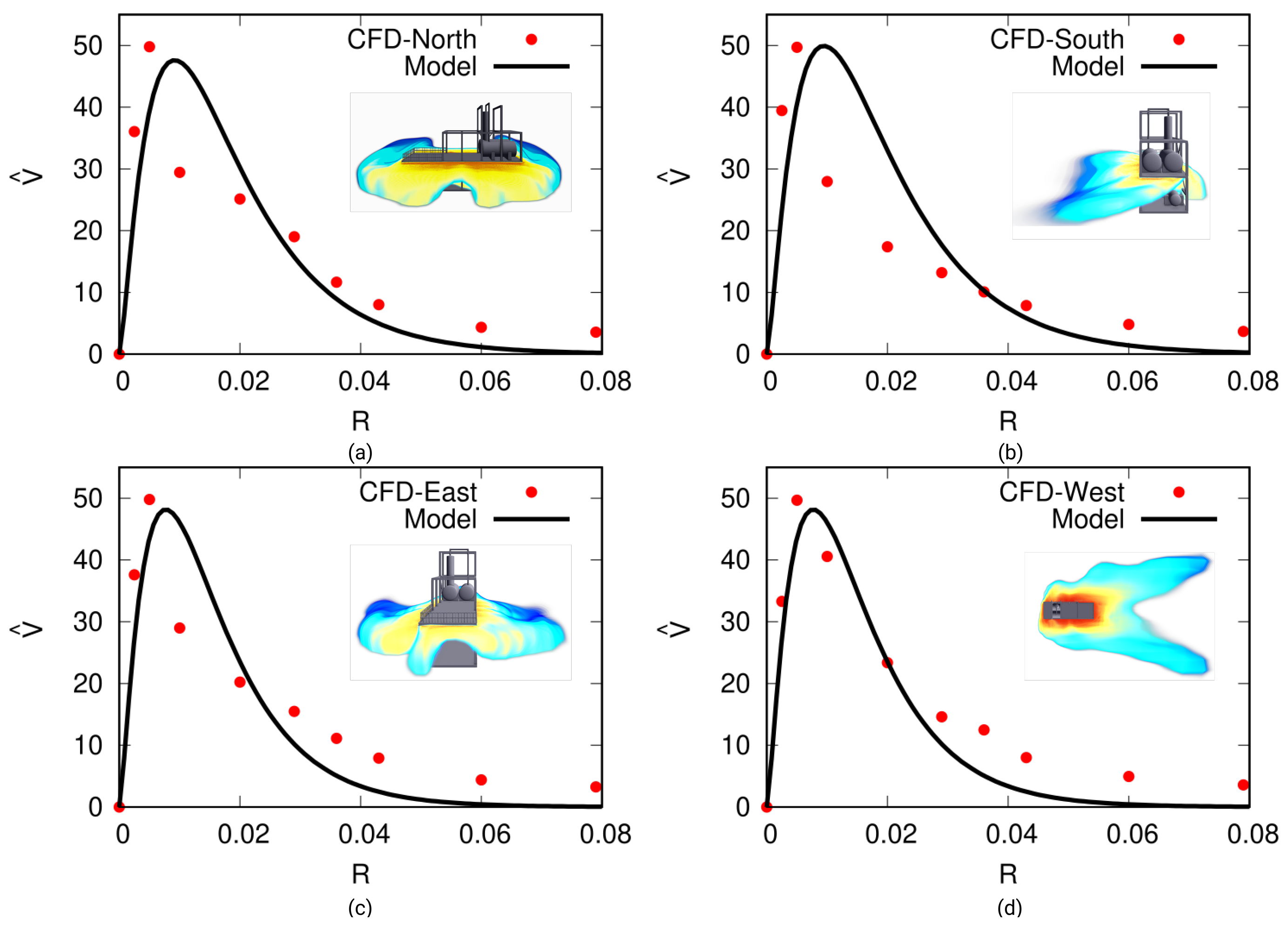


Comparison with CFD suggests the following:

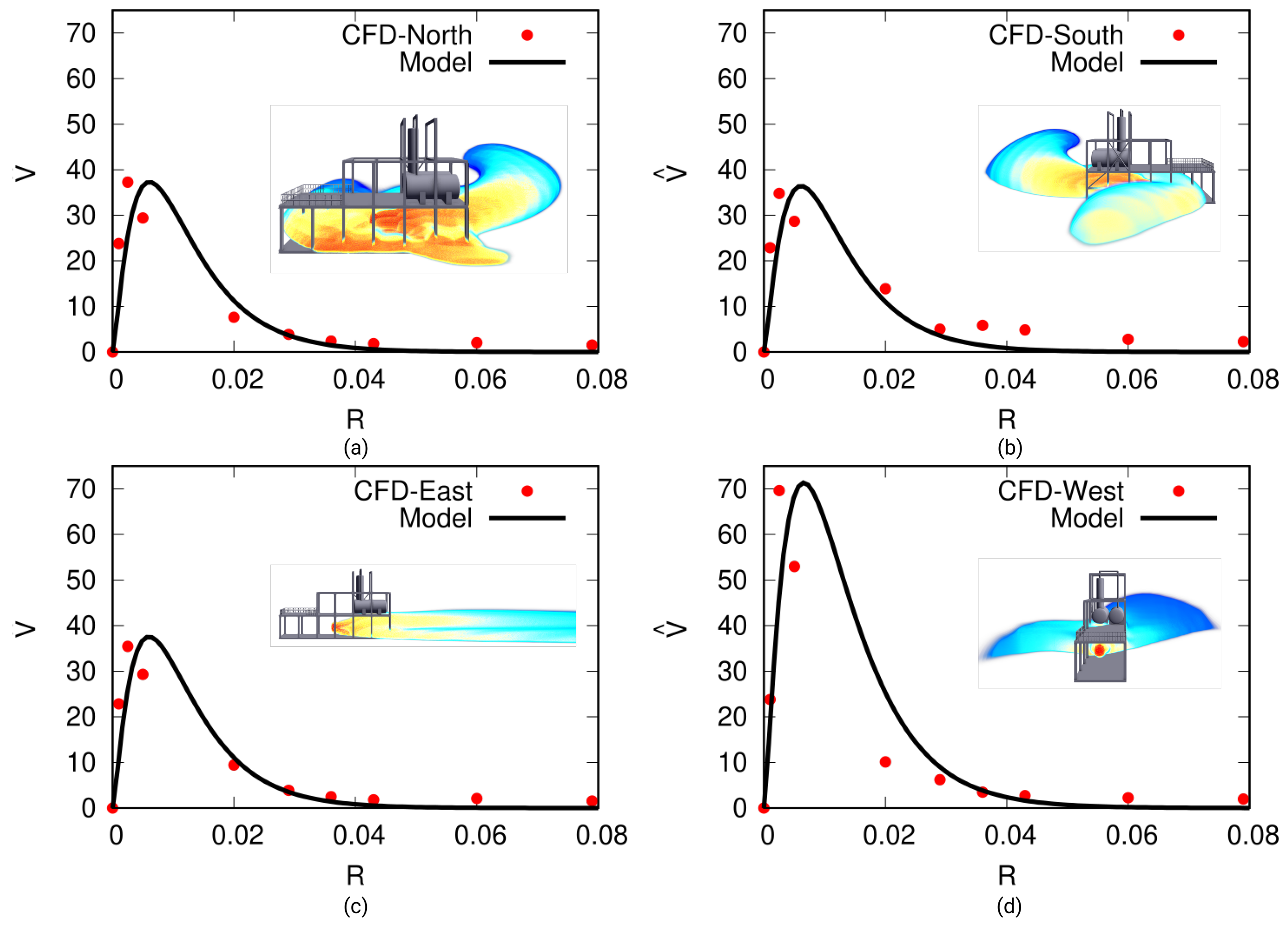
$$\hat{V} = A^m R^n \exp\left(-BR^{0.8}\right)$$

where m = n = 1.5

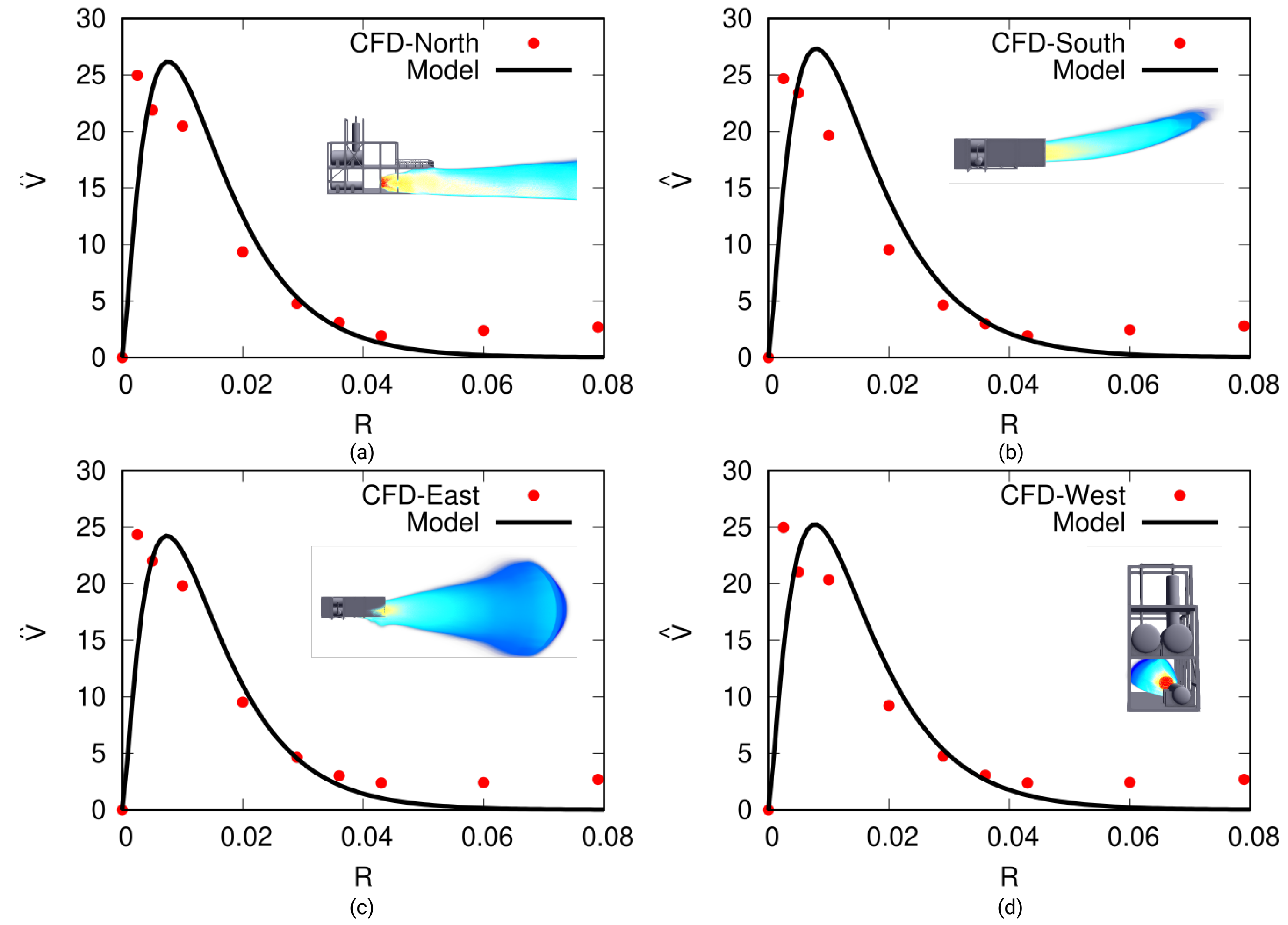
Results



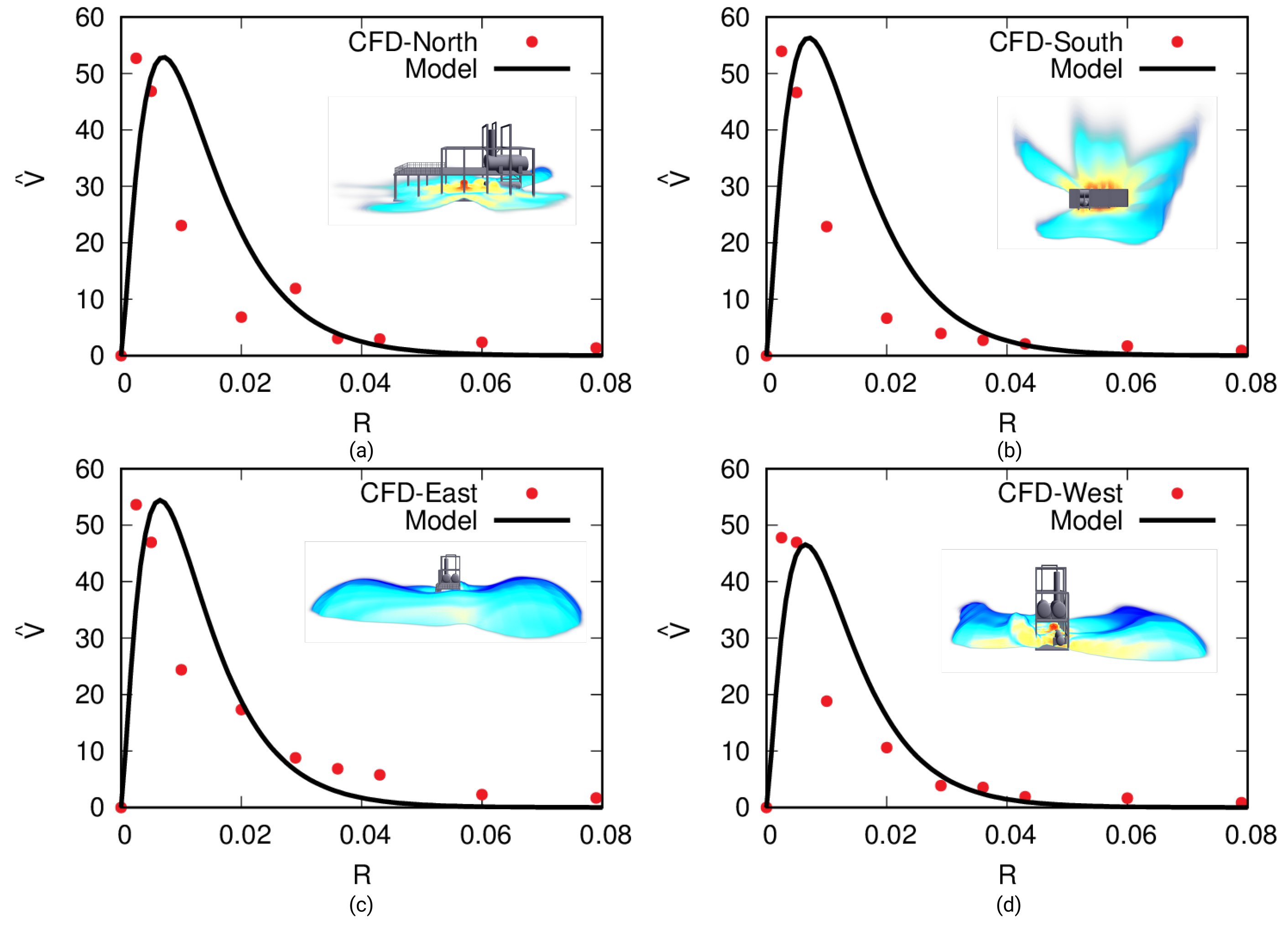
Up



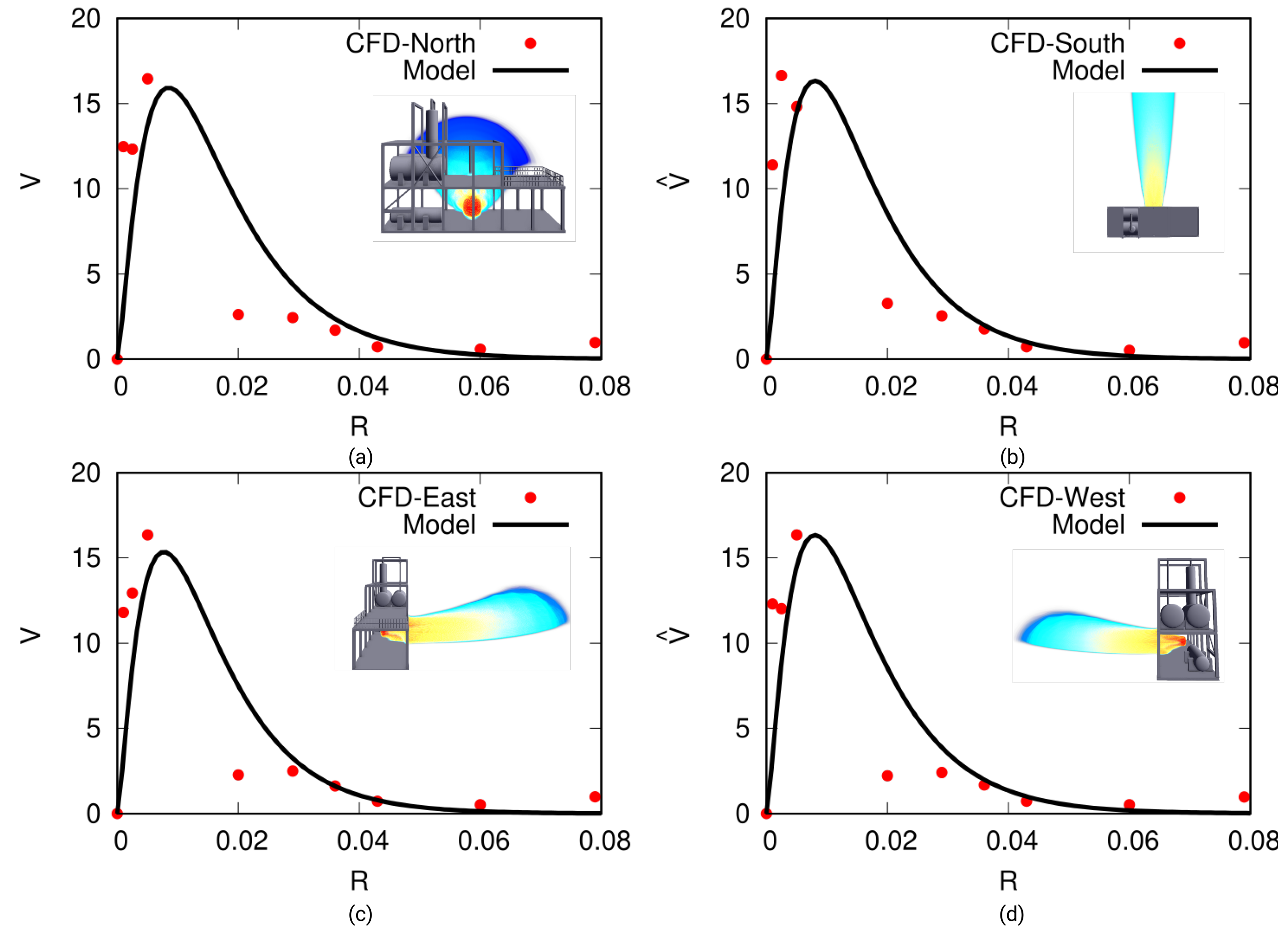
West



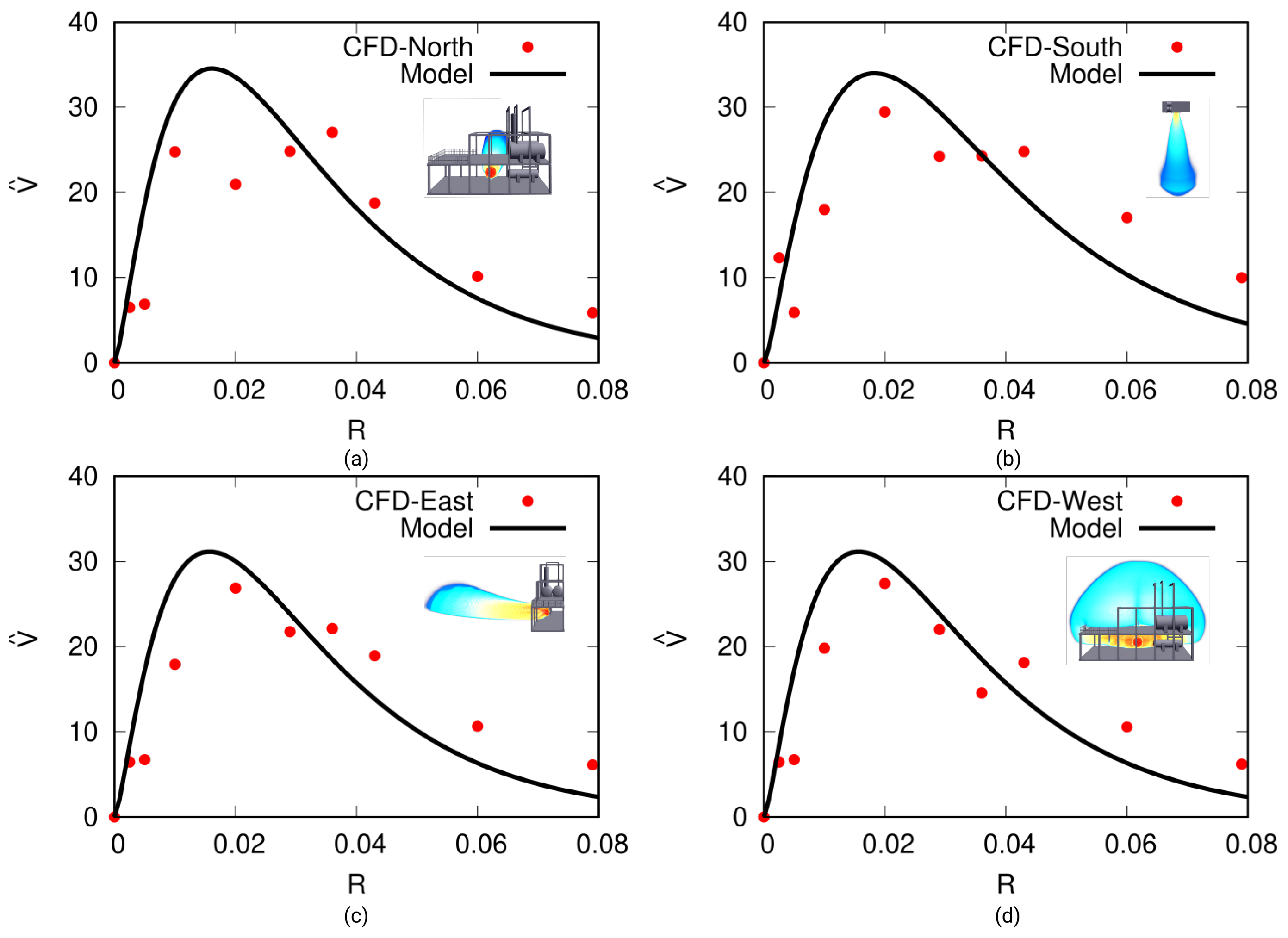
East



Down

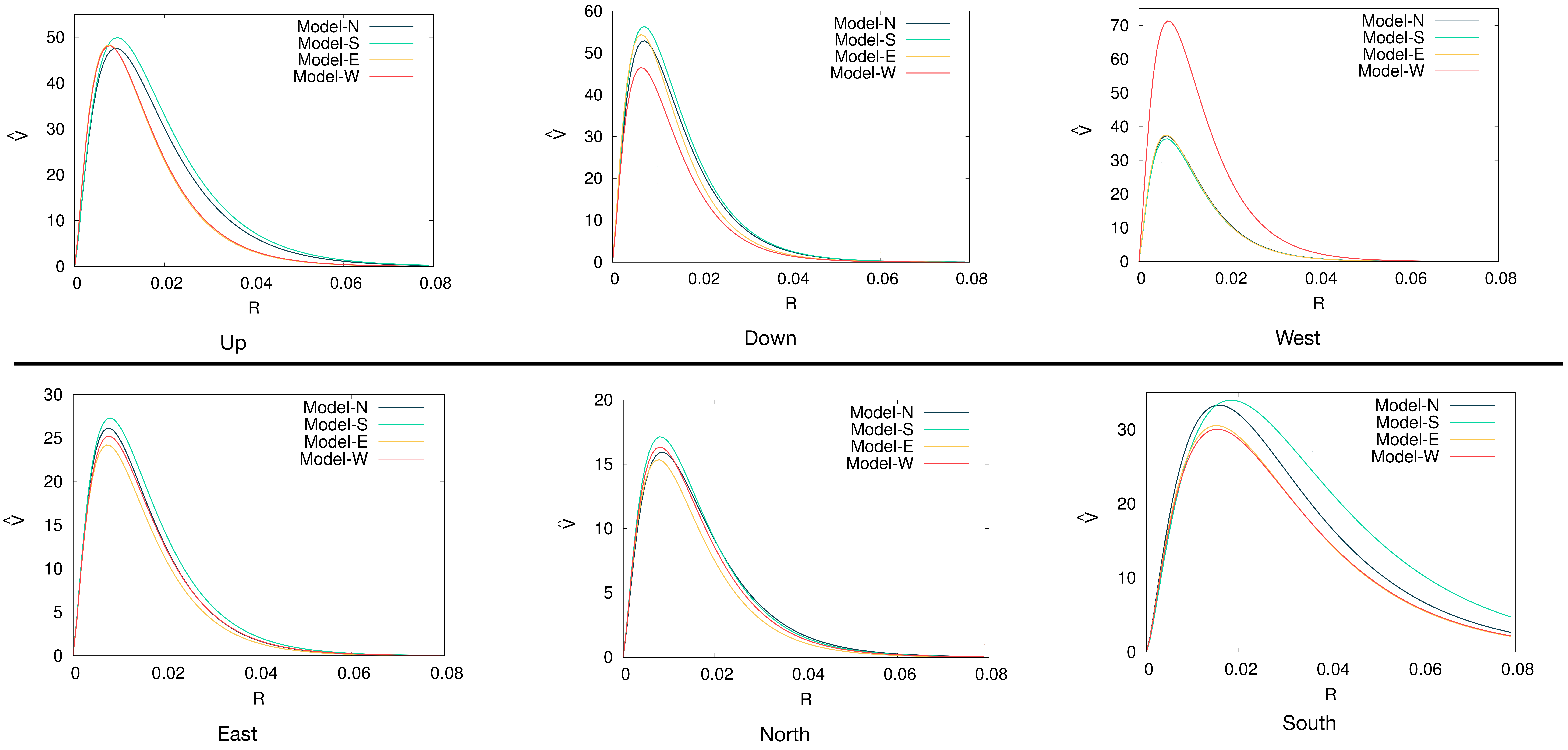


North

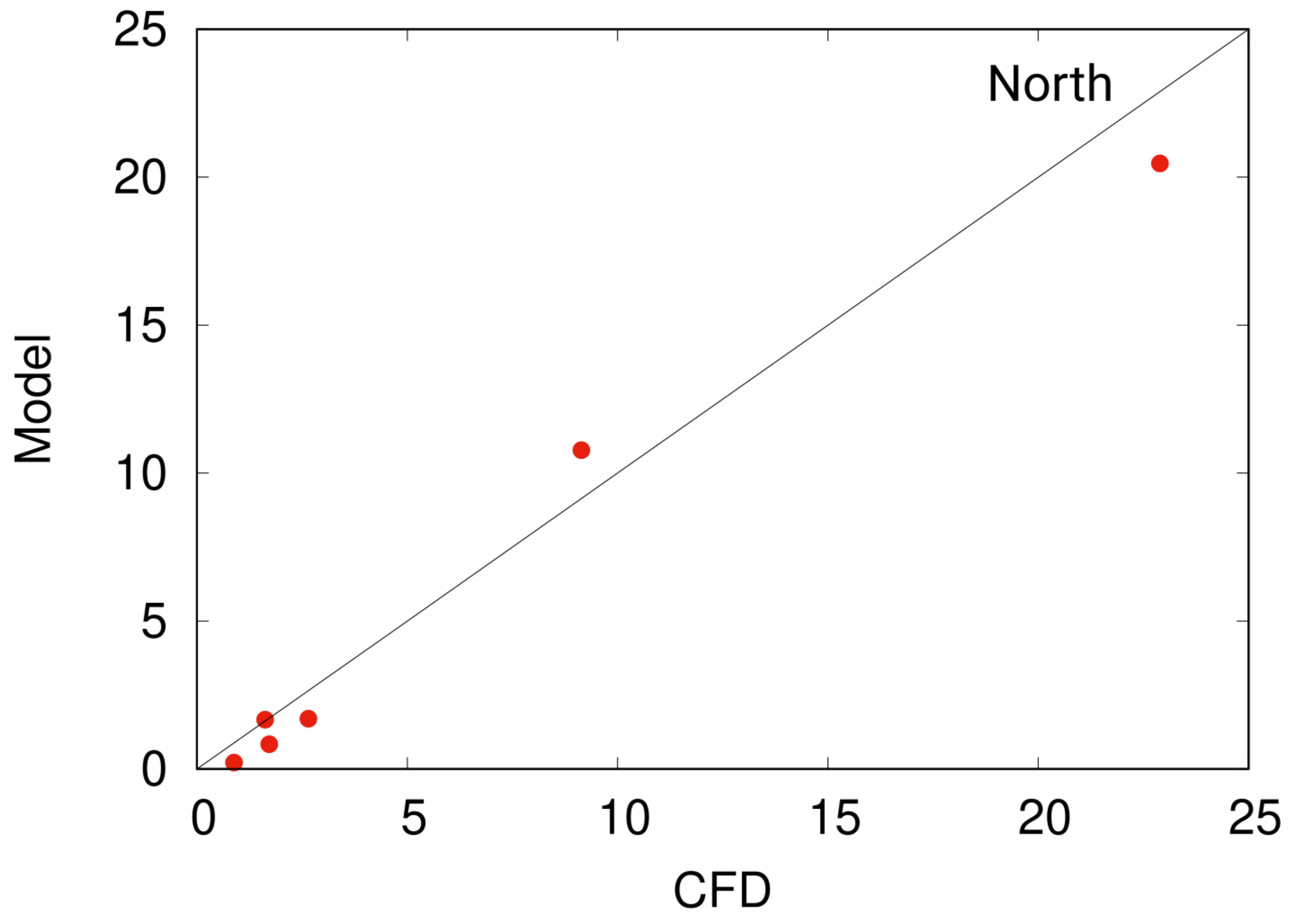


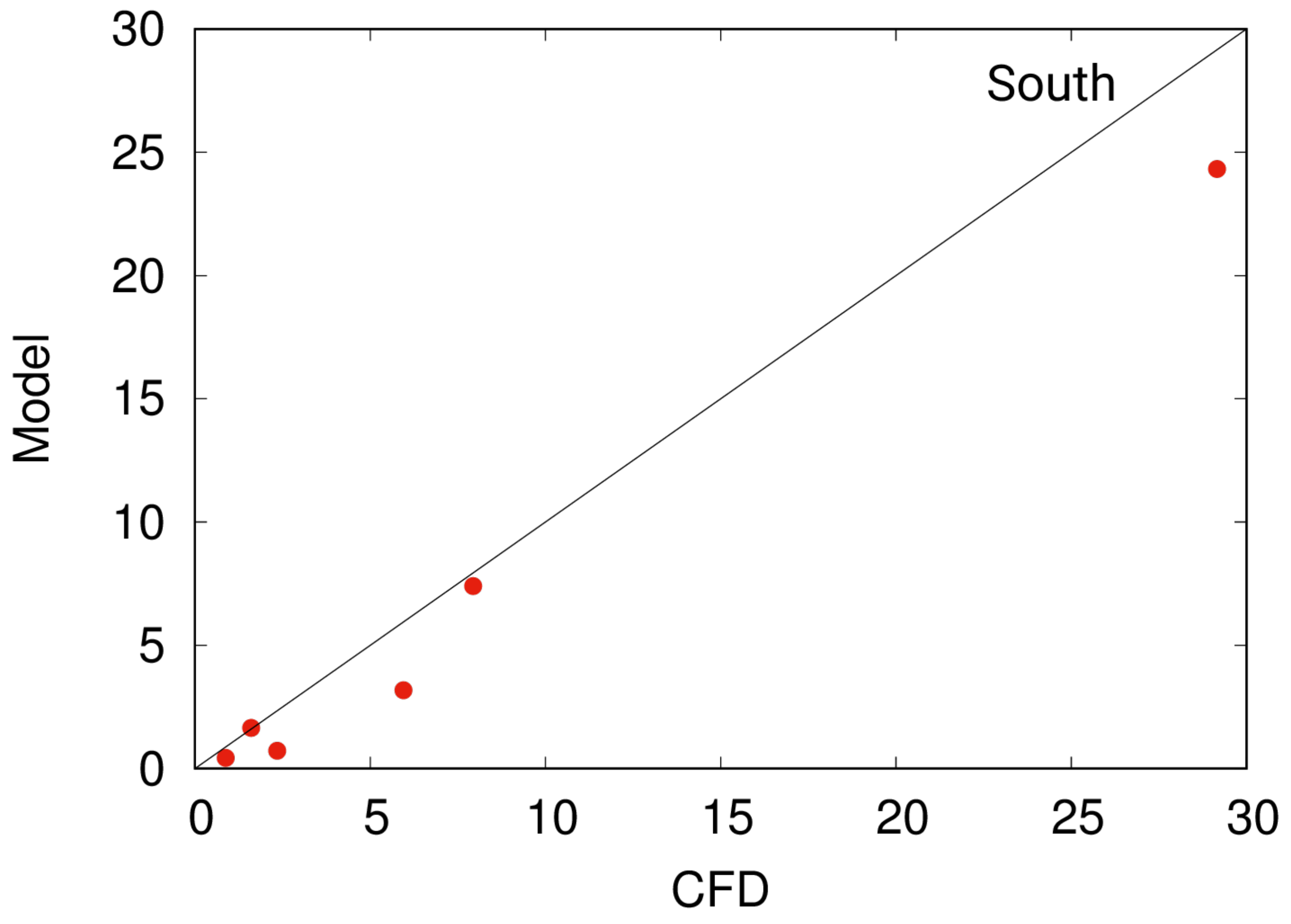
South

Results

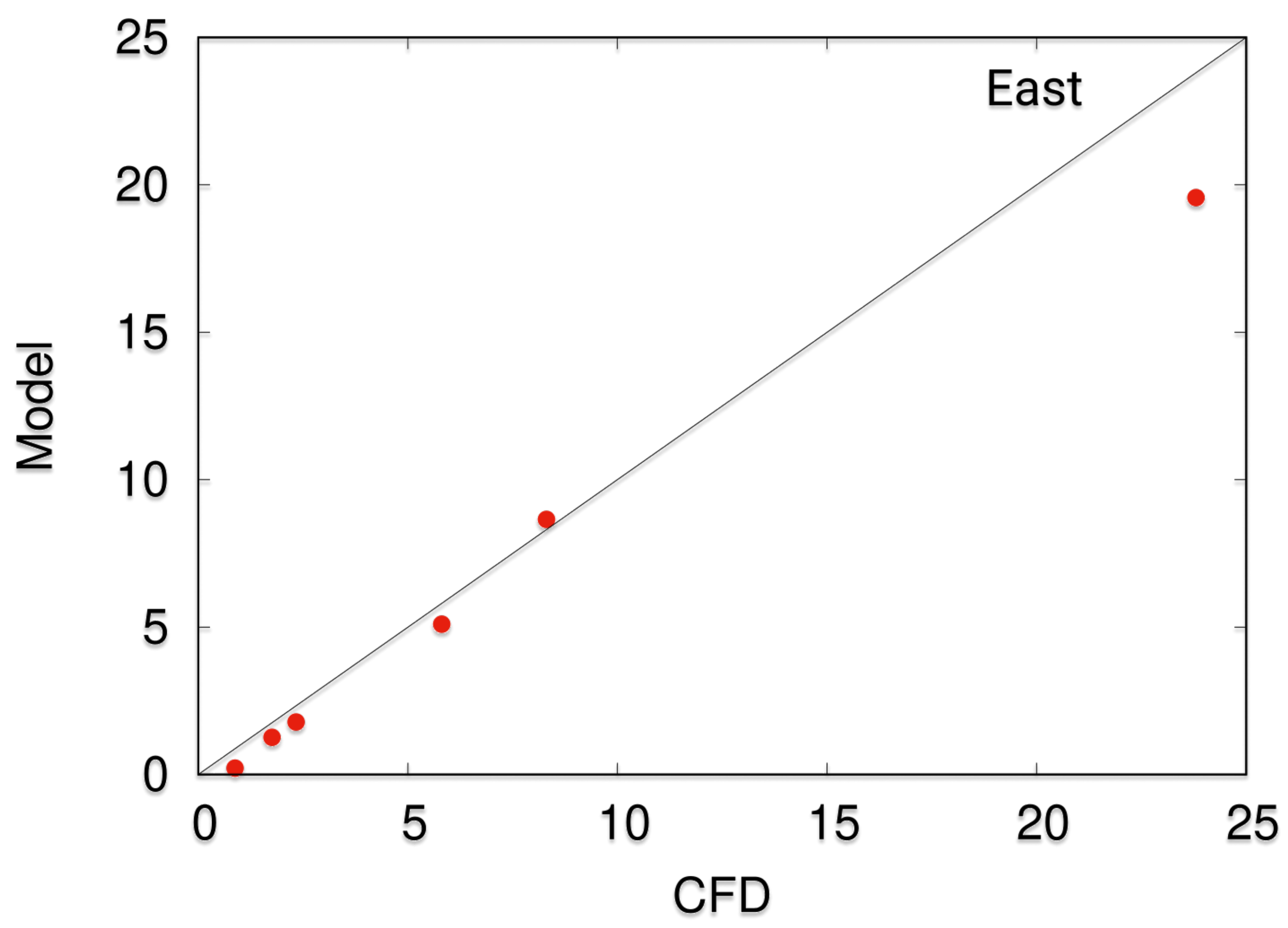

Model-N
Model-S
Model-E
Model-W
$\hat{V}$
R
Up
Down
West
East
North
South

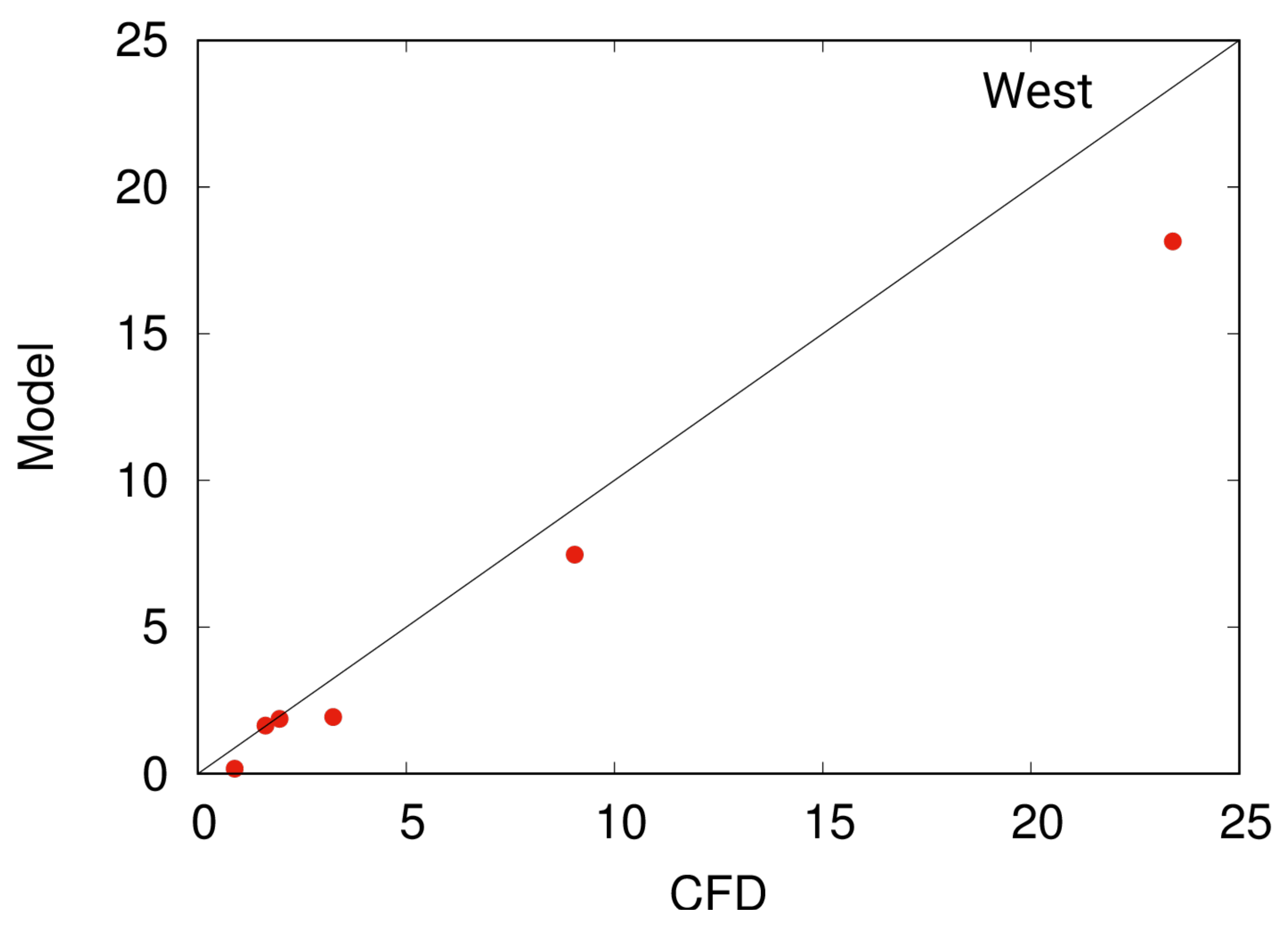
Results - Validation

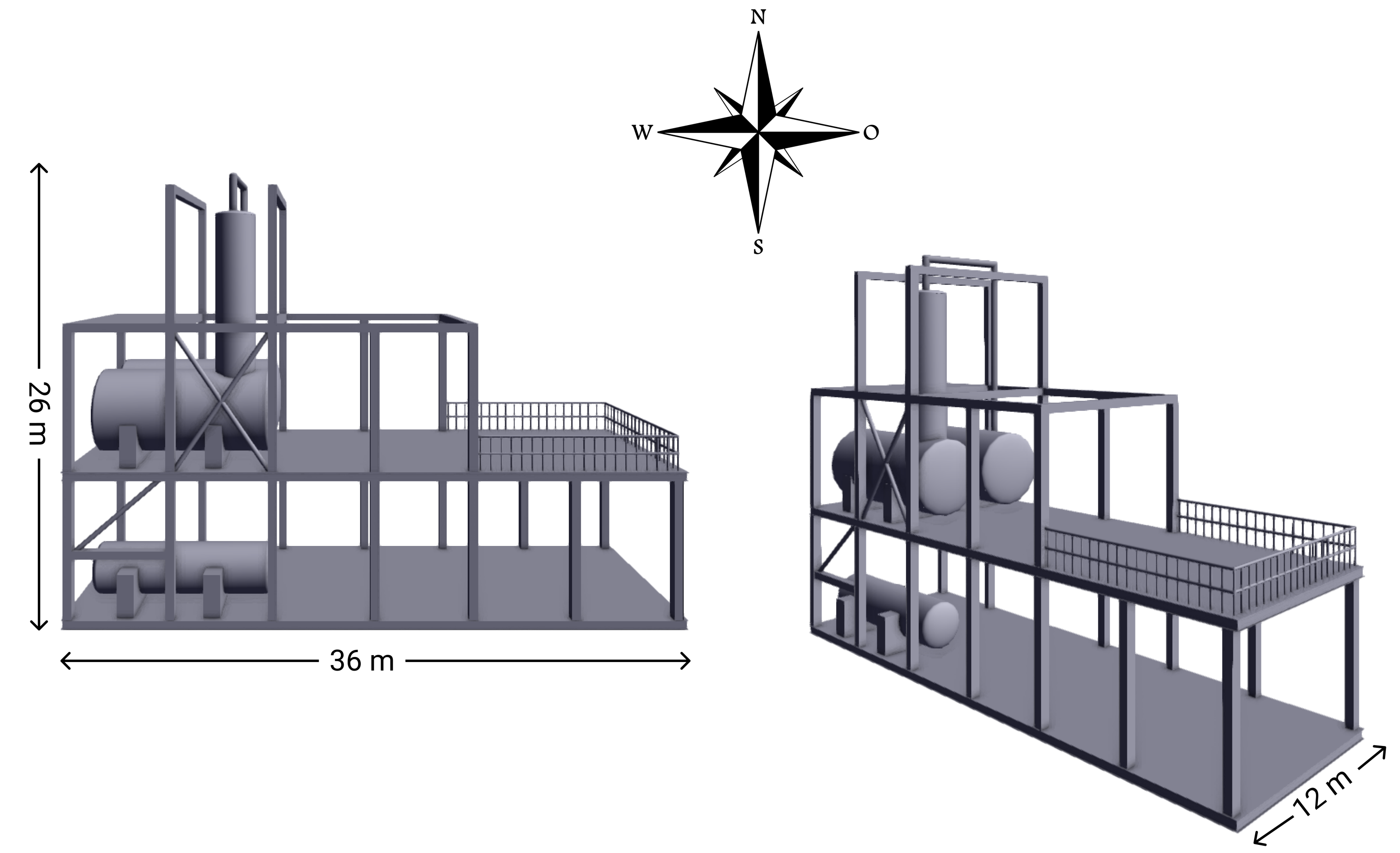




- A new set of CFD simulation was used in the validation process
- Overall good agreement was observed







Results

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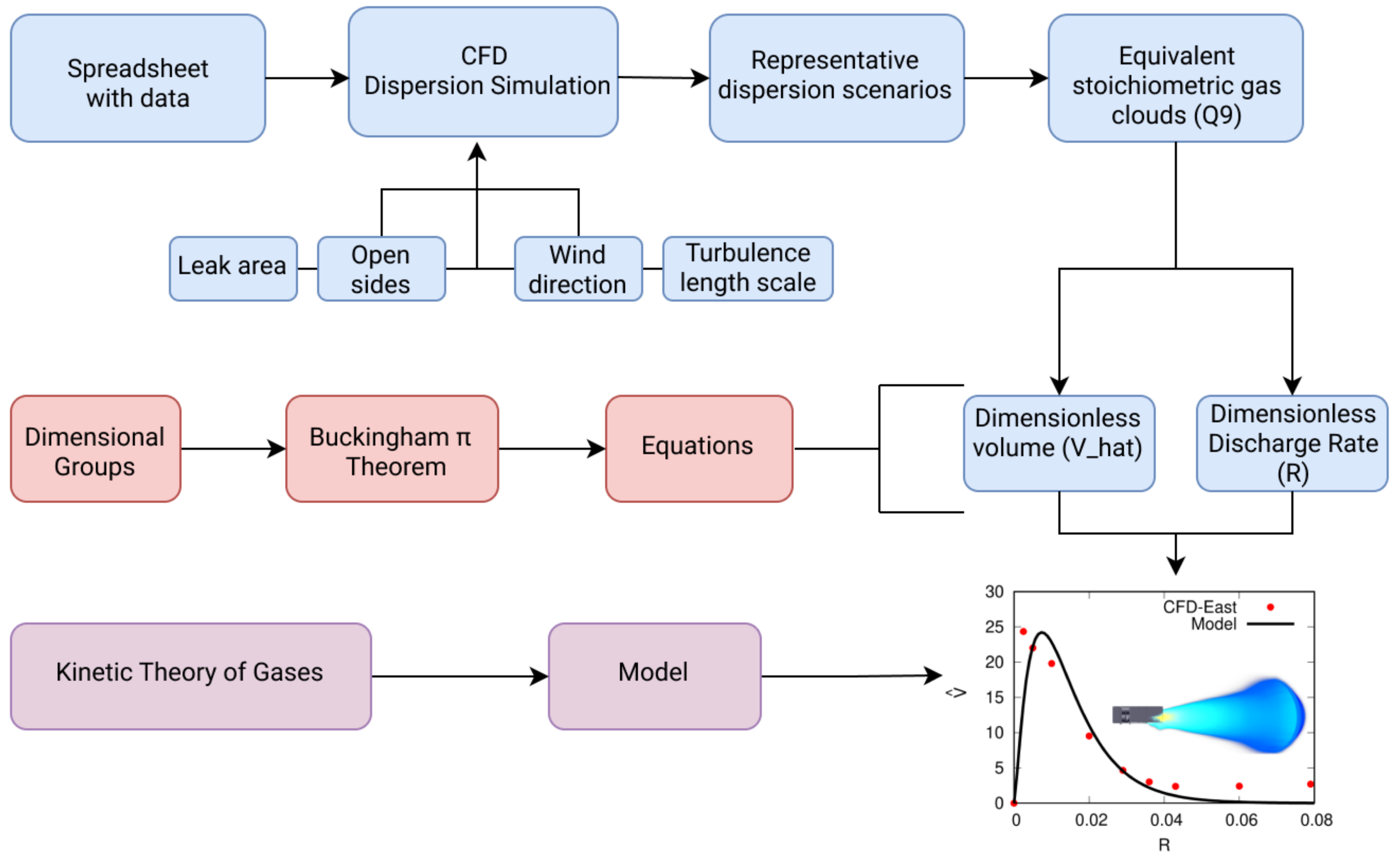
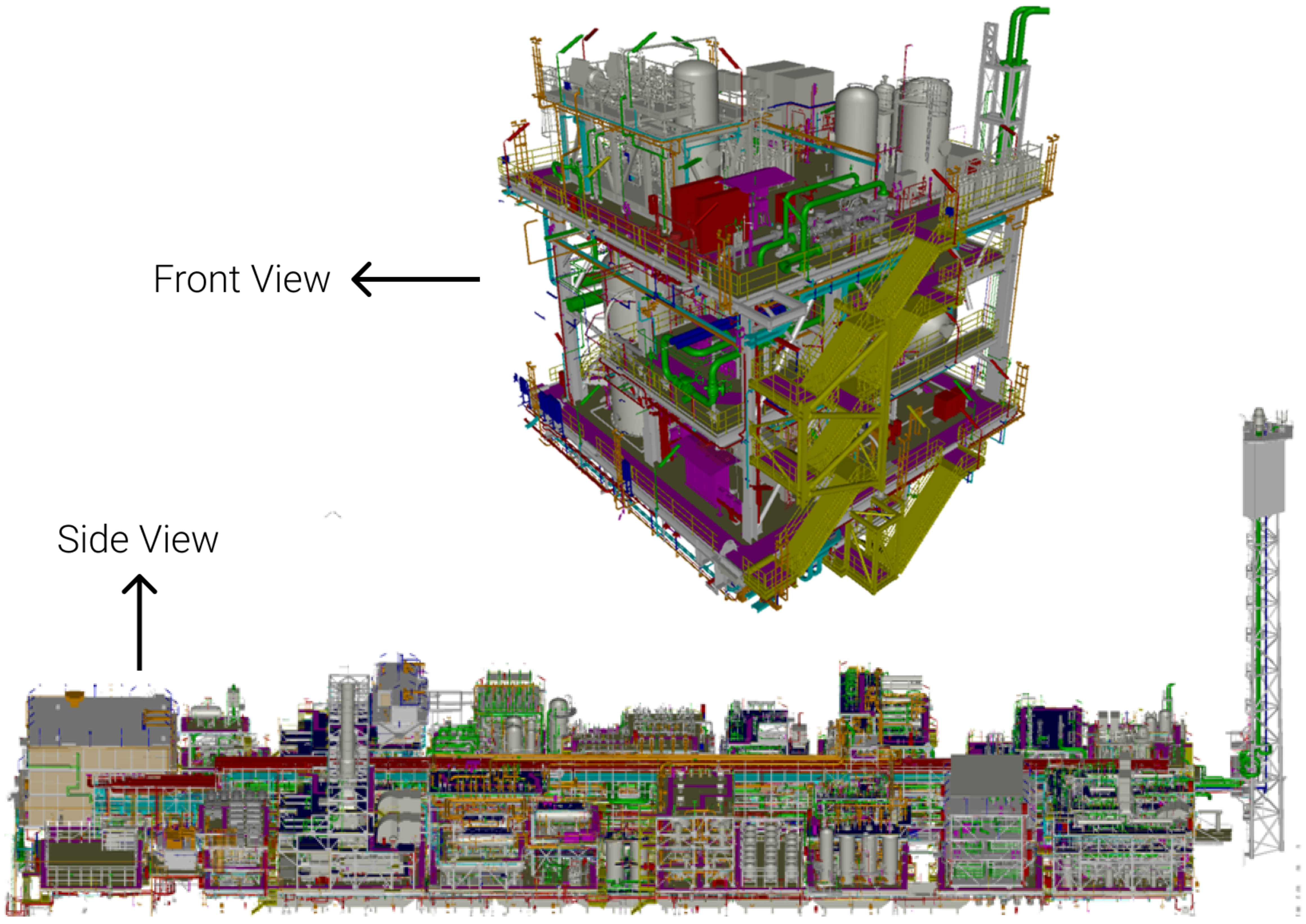
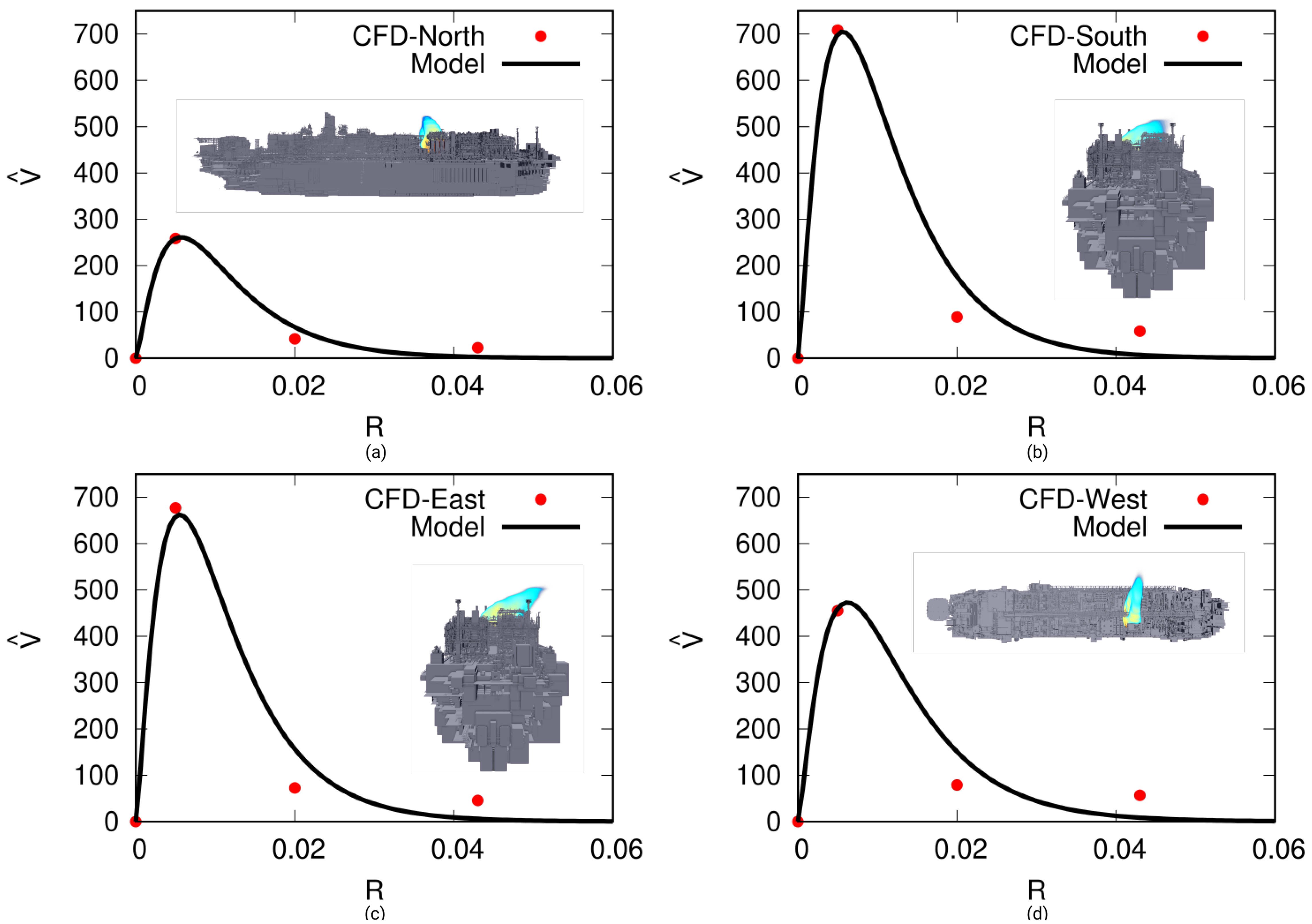
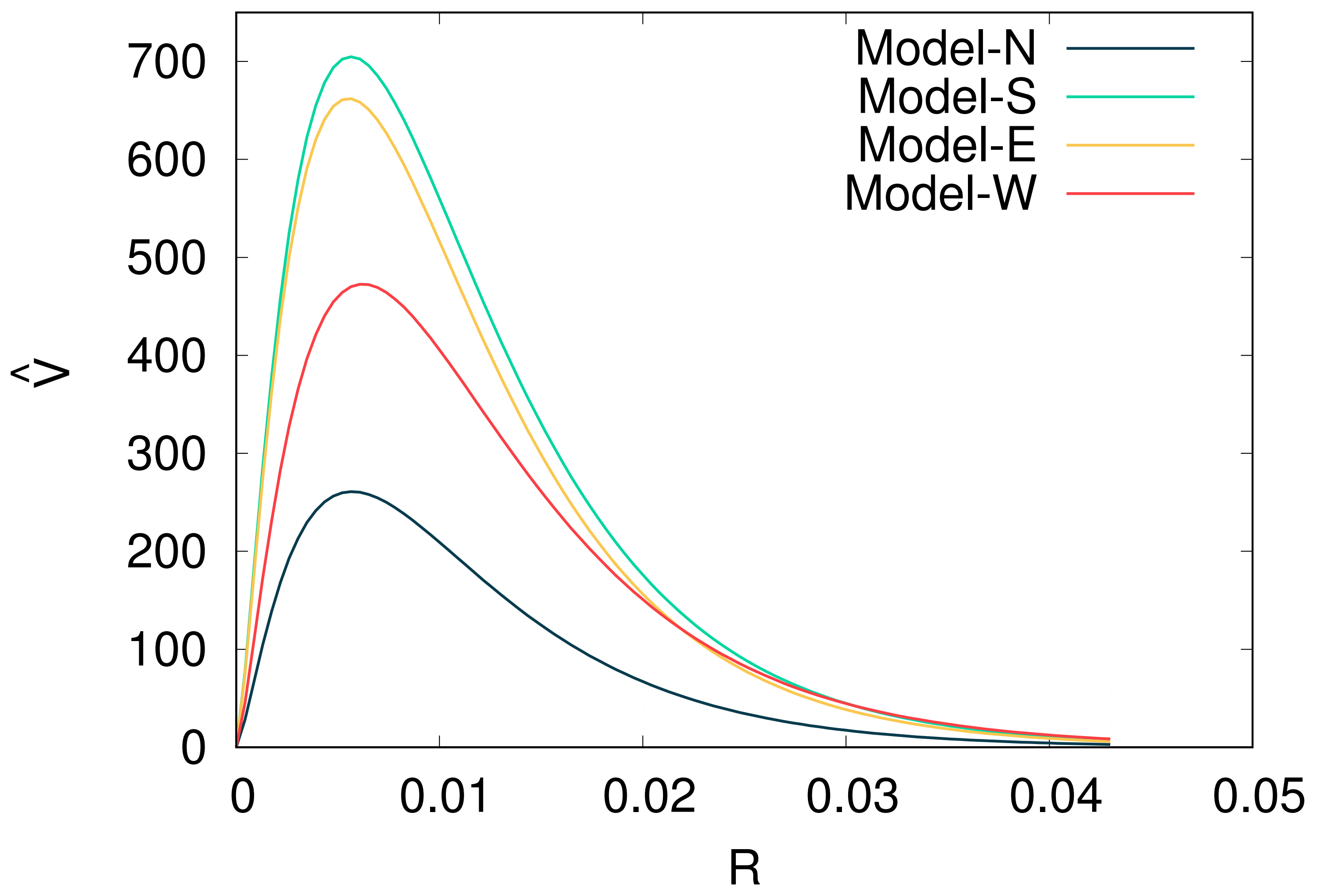


Results - Engineering case



Petrobras - FPSO

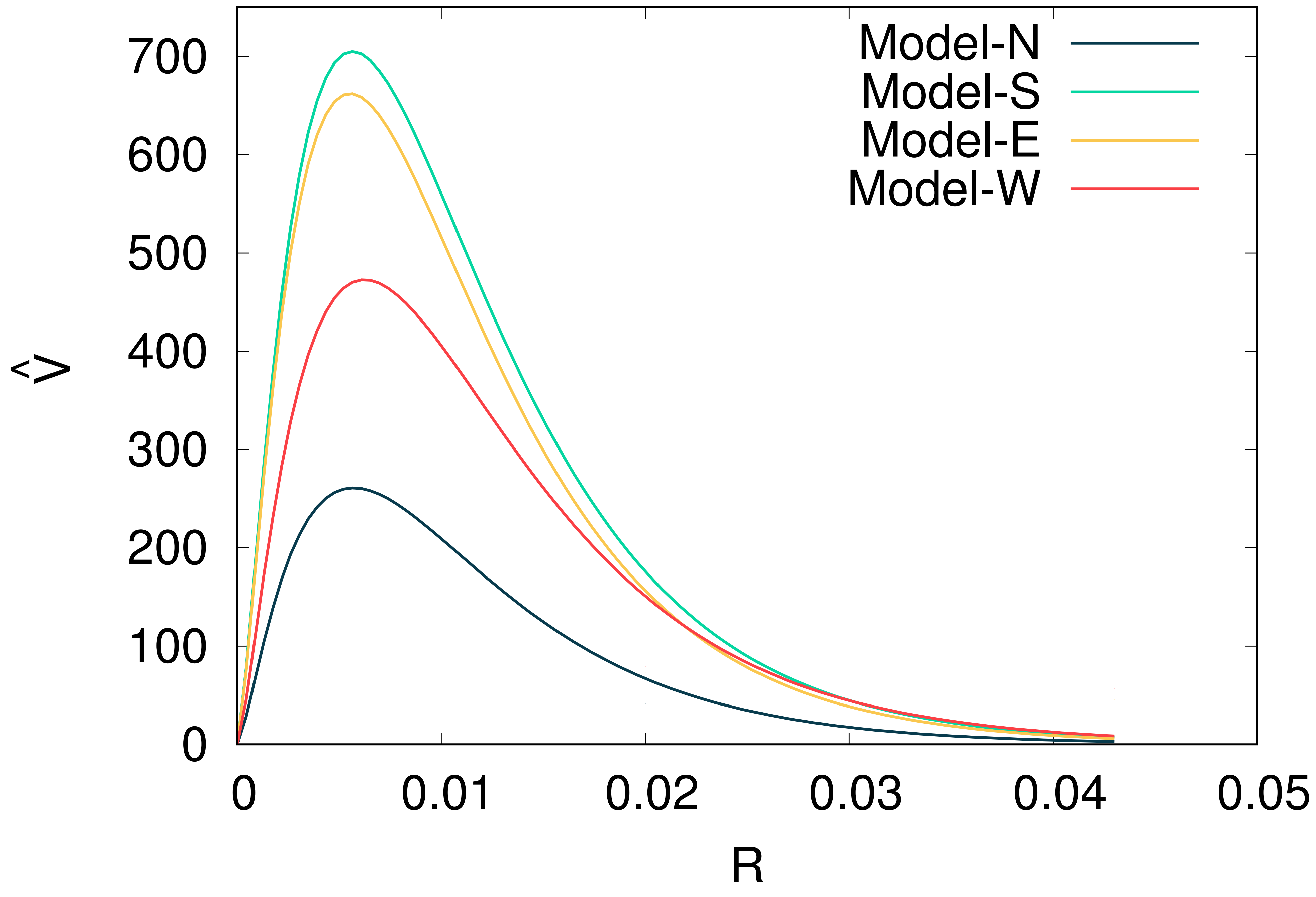


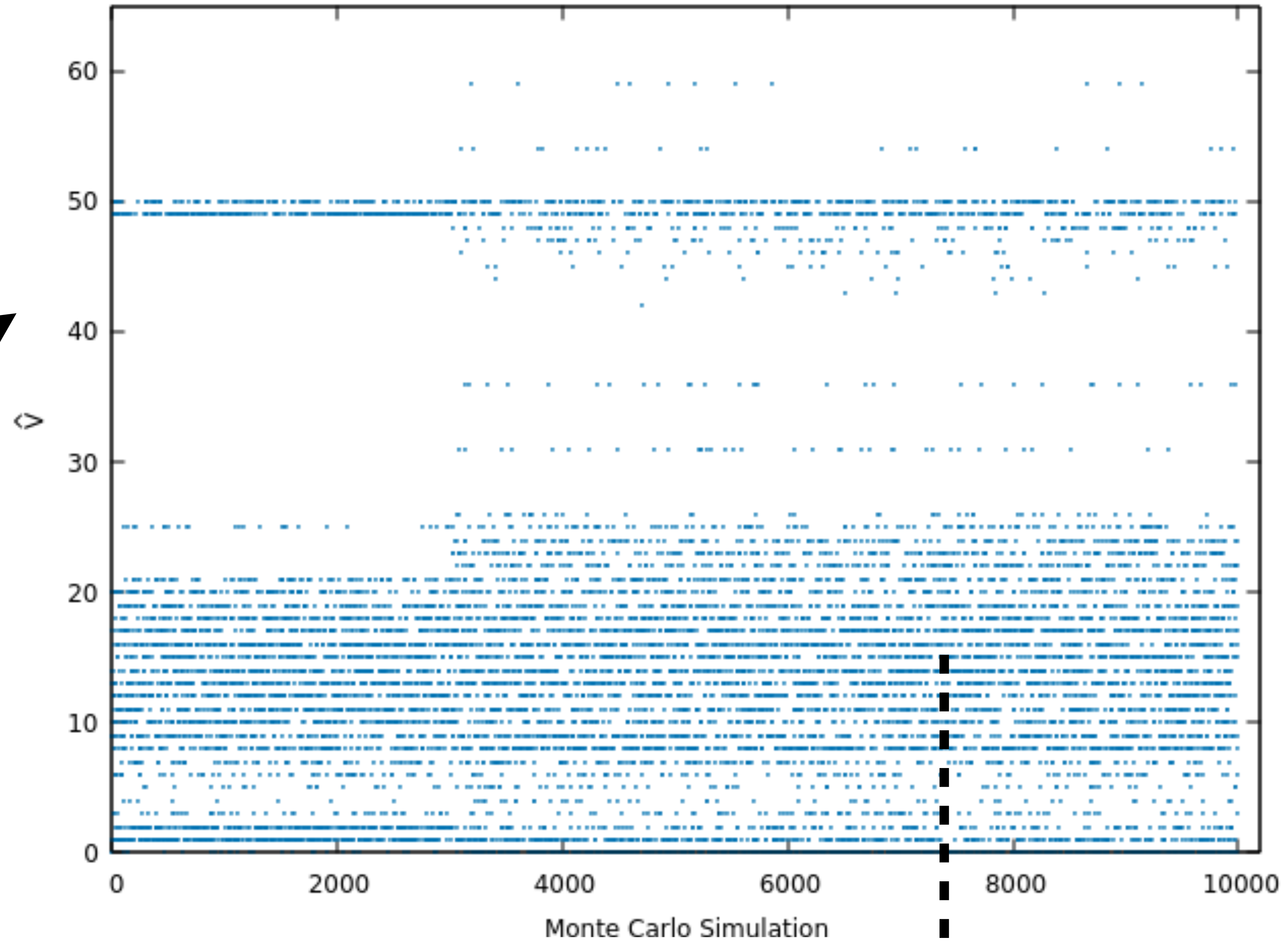


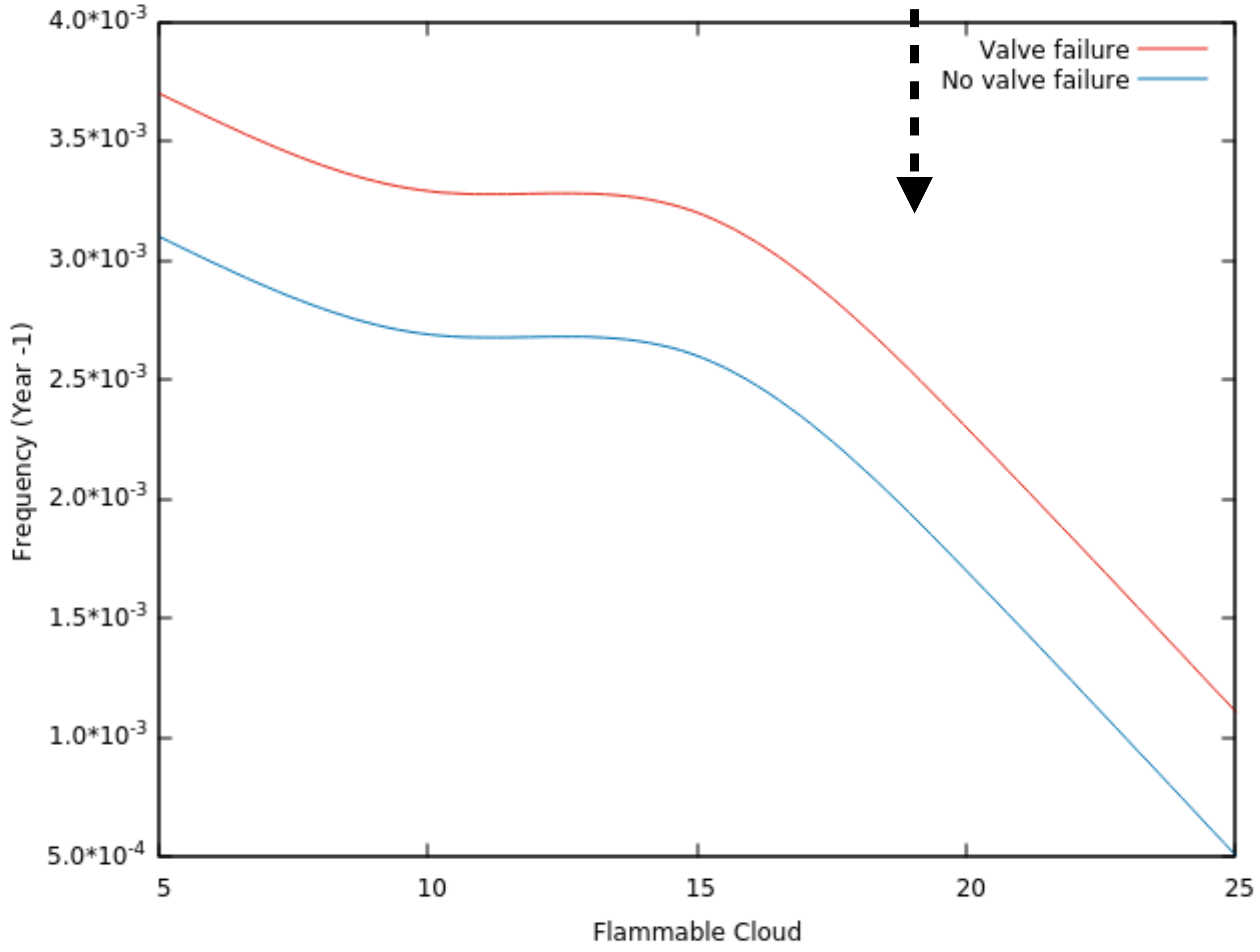
Results - Applications

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

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







Closing remarks

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McPeas - Monte Carlo Probabilistic Explosion Analysis Simulator

Acknowledgments

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PETROBRAS

CAPES

prh Programa de Recursos Humanos da ANP

anp Agência Nacional do Petróleo, Gás Natural e Biocombustíveis

dpr simulations