Wind-driven rain CFD analysis for roof drainage design: a case study of the Riverside Museum, Glasgow

N. P. O'Sullivan [1], E. Cardone [2], N. Truong, A. W. Rofail

[1] *Windtech Consultants, London, United Kingdom, niall@windtechglobal.com*
[2] *Windtech Consultants, London, United Kingdom, edoardo@windtechglobal.com*

SUMMARY
This paper explores the application of Computational Fluid Dynamics (CFD) for Wind-Driven Rain (WDR) analysis in the design and optimisation of roof drainage systems. Conventionally, WDR assessments have relied on wind tunnel experiments, which are costly and inflexible. CFD offers a more detailed and adaptable method by resolving the interaction between airflow, rain transport, and building geometry. A case study is presented for a complex roof structure in Glasgow, where WDR simulations were used to evaluate rain accumulation across roof panels. Flow Rate (Q) and Flow Rate Ratio (FRR) were employed to quantify localised intensification of rain loads. Results indicate that wind effects can significantly increase drainage demand in exposed areas, exceeding standard design assumptions. The study demonstrates that CFD-based WDR analysis provides a robust basis for targeted gutter sizing, reducing the risk of overflow while avoiding unnecessary overdesign.

Keywords: Computational Fluid Dynamics (CFD), Wind Driven Rain (WDR), Gutter Design.

1. Introduction

Computational Fluid Dynamics (CFD) is a powerful tool that has been used extensively in the design and development of the urban built environment, particularly in wind-structure interaction, such as natural ventilation and pedestrian comfort. Another less commonly explored, but effective application of CFD is in wind-driven rain (WDR) analysis. WDR plays a critical role in the moisture performance of building envelopes and roof drainage systems, particularly in complex geometries where wind effects can significantly alter rain distribution. Conventional methods typically rely on simplified rainfall assumptions, which do not account for localised amplification caused by wind patterns. This paper presents the application of CFD to assess WDR behaviour and inform gutter design for the Riverside Museum development in Glasgow. The study demonstrates how CFD can provide a detailed, spatially resolved understanding of rain accumulation.

1. Method

A steady-state Computational Fluid Dynamics (CFD) approach was adopted to simulate airflow and wind-driven rain (WDR) behaviour. The airflow field was resolved using the Reynolds-Averaged Navier–Stokes (RANS) equations, which provide a time-averaged representation of turbulent flow. Turbulence closure was achieved using the k-ω model. The turbulence model coefficients were calibrated against Windtech's boundary-layer wind tunnel measurements for pedestrian wind comfort assessments. Rain transport was modelled using a decoupled Eulerian approach, in which the rain phase is treated as a continuous scalar field transported within the airflow. This method assumes that raindrops are influenced by the precomputed wind field but do not affect the airflow itself, which is a valid assumption for typical rain intensities where momentum coupling is negligible. A droplet size distribution was defined based on established empirical relationships, representing a spectrum of raindrop diameters rather than a single size. Table 1 shows the corresponding drop diameters for a rain intensity of 144 mm/hr, derived from the empirical formulation of Best (1950).

Table 1. Rain Distribution Parameters

Rain Percentile		5th Percentile	25th Percentile	50th Percentile	75th Percentile	95th Percentile
Rain intensity	mm/hr	144	144	144	144	144
Rain Drop Diameter	mm	1.19	2.41	3.54	4.82	6.92
Terminal Velocity	m/s	2.182	4.902	7.618	10.852	16.426
Phase Fraction Value	-	1.089E-06	1.628E-06	1.314E-06	9.228E-07	4.879E-07
Density	kg/m3	1000	1000	1000	1000	1000

The roof geometry was discretised into a series of panels to enable spatially resolved analysis. For each panel, rain accumulation was quantified in terms of absolute Flow Rate (Q) and Flow Rate Ratio (FRR). The flow rate is used to define FRR, which effectively models how wet different areas of the site will get depending on the amount of sheltering.

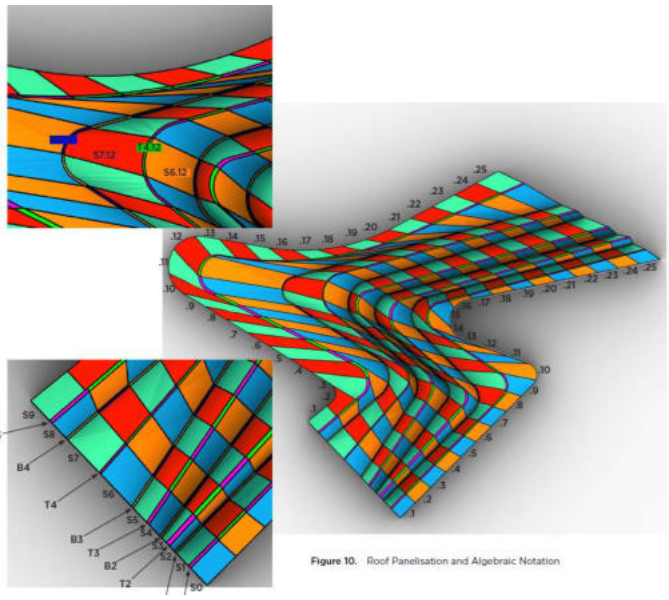

Figure 1. Roof Panelisation and Algebraic Notation

The following equations are defined:

$$\dot{N}_{ref,v} = \frac{Q_{ref,v}}{A_{ref}} \quad (1)$$

$$\dot{N}_{\theta,v} = \frac{\dot{Q}_{\theta,v}}{A_{H0}} \quad (2)$$

Equation 1 returns the reference mass flux, that is the flux calculated at an unsheltered reference area in the surrounds, for a given wind speed scenario 'v'. Equation 2 returns the flux for a given roof panel with inclination 'θ' and wind speed scenario 'v'. It is worth noting that A_{H0} refers to the projected horizontal area of the roof panel. The rain flow rate is then normalised to create the Flow Rate Ratio using the results from the equations above:

$$FRR_{\theta,v} = \frac{\dot{N}_{\theta,v}}{\dot{N}_{ref,v}} \quad (1)$$

This is used to quantify the wind-driven-rain effects, for isolated wind directions. The maximum FRR and Q are extracted from all wind directions for each panel region and shown in the results section. The building model and the segmented roof area are shown in Figure 1. Algebraic notation is used to identify each panel.

2. Results

Results for the 50th and 95th percentile wind conditions are presented in Figures 2 and 3, respectively. The CFD simulations show significant variability in wind-driven rain (WDR) accumulation across the roof, with both Flow Rate Ratio (FRR) and absolute flow rate (Q) providing complementary insights into the underlying behaviour. FRR highlights the extent of wind-induced rain accumulation relative to an unsheltered reference condition. Under 50th percentile winds, FRR values range from approximately 1.0 in sheltered regions to 3.8 in exposed panels, increasing to over 6.3 under 95th percentile conditions. The highest amplification occurs predominantly on the inclined S-series panels at the southwestern region of the roof, where wind direction and geometry are critical factors. In contrast, Q represents the absolute drainage demand and is strongly influenced by panel area. Panels with high FRR values do not necessarily generate the highest flow rates if their contributing area is small. Conversely, large panels with only moderate FRR can produce the highest absolute flows. This is clearly demonstrated by panel S8.12, which records the highest flow rates in the dataset (i.e. 7.91 kg/s at 50th percentile and 10.59 kg/s at 95th percentile) despite relatively modest FRR values (i.e. 1.05 and 1.40, respectively). The comparison between wind percentiles highlights the non-uniform response of the roof. The rain amplification is significantly greater for inclined surfaces, particularly within the S-series. In contrast, the lower B-series panels remain close to FRR ≈ 1.0 across both scenarios, indicating minimal sensitivity to wind effects due to shielding.

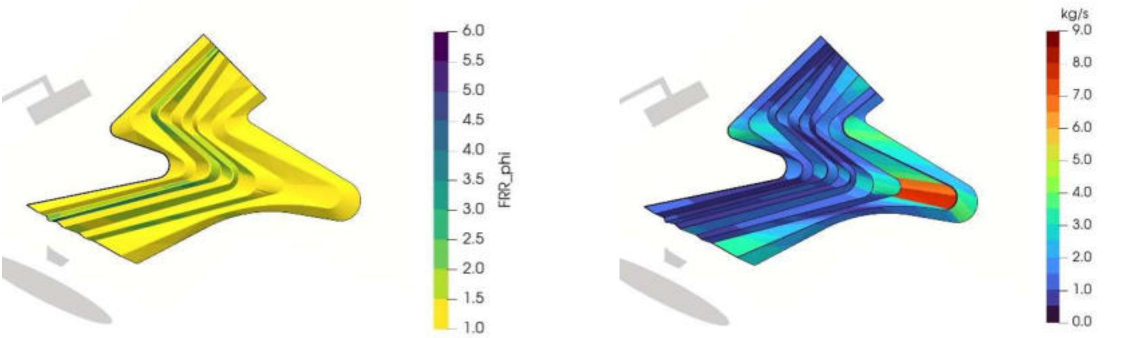

Figure 2. Maximum Flow Rate Ratio (left) and absolute Flow Rate (right) results for 50th winds

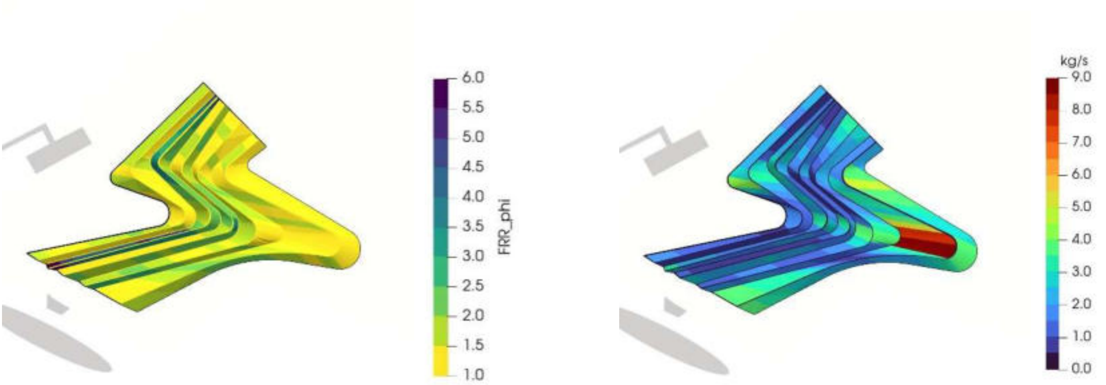

Figure 3. Maximum Flow Rate Ratio (left) and absolute Flow Rate (right) results for 95th winds

3. Discussion

The results highlight the importance of considering both Flow Rate Ratio (FRR) and absolute Flow Rate (Q) when interpreting wind-driven rain (WDR) behaviour. Q captures the total volume of water collected and therefore provides the most relevant metric for gutter sizing and drainage design. FRR provides a normalised measure of wind-induced rain accumulation, identifying areas where airflow significantly redistributes rainfall. High FRR values, particularly observed in the inclined S-series panels, indicate zones where wind effects actively concentrate rainfall onto surfaces that would otherwise receive lower exposure. These findings represent a key advantage of CFD modelling of wind-driven rain, since localised amplification effects cannot be captured using conventional design methods. However, panels with high FRR do not always correspond to the highest drainage loads due to their relatively small contributing areas, while large panels with moderate FRR can generate the highest flow rates, as clearly illustrated by panel S8.12. The comparison between 50th and 95th percentile wind scenarios further emphasises the non-linear and geometry-dependent nature of WDR effects.

4. Conclusion

This study demonstrates that CFD simulations of WDR provide a robust and spatially detailed methodology for informing gutter and drainage design in complex building geometries. By resolving the interaction between wind, rain, and surface geometry, the presented approach captures both the redistribution and accumulation of rainfall across the roof. The results show that wind effects can significantly increase rain accumulation in exposed and inclined regions. However, the highest drainage demands are still strongly influenced by the contributing surface area. Overall, the results show that while Q provides the primary metric for drainage design, FRR can be particularly useful for identifying wind-driven redistribution of rainfall. Finally, the findings demonstrate that traditional drainage design methods based on uniform rainfall assumptions may significantly underestimate peak conditions in critical areas, whereas CFD enables targeted design interventions.

REFERENCES

Best, A.C. (1950). The size distribution of raindrops. *Quarterly Journal of the Royal Meteorological Society*, 76(327), 16–36.