THE EFFECT OF WIND-DRIVEN RAIN ON CLADDING PRESSURE OF BUILDINGS UNDER WIND AND RAIN CONDITIONS

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Abstract. It is a common occurrence that wind and rain occurs together. During phenomena such as thunderstorms, hurricanes, typhoons and other storms, wind is usually accompanied by rain. In regions like the tropic, the rain is especially heavy. It has long been an uncertainty as to how much does the rain contributes towards increasing the wind pressure on the cladding. This paper attempts to answer this question by using computational fluid dynamics techniques to obtain the pressure due to raindrops impinging on building faces.

Recently, with the advancement of computational fluid dynamics a better understanding of wind-driven rain and the interaction of wind, rain and building can be established. This paper proposed a framework for the calculation of the increase of pressure on building faces due to wind-driven rain. The method takes into consideration of the local effect of wind flow around the building on the raindrops, the trajectory of raindrops close to the building, velocity of raindrops hitting the building face and intensity of wind-driven rain on the building face. Calculations are done on a rectangular building. The increase in pressure on the building faces due to the effect of wind-driven rain is obtained. It is found that the increase is very small for hourly average pressure over a large area of the cladding. However for a shorter duration, say of 1-minute and over a 1.0m square cladding, the increase can be 6%-7% of the dynamic wind pressure.
1 INTRODUCTION

When wind and rain occur together, the raindrops are blown by the wind and move in a slanting manner. As the raindrops impact onto the building façade, the momentum of the raindrop will be converted to force acting on the cladding. Thus, besides the wind pressure, there will be certain extra pressure acting on the cladding due to the effect of wind-driven rain. In places like the tropic where the rain is specially heavy, it has been surmised that the pressure due to the raindrops hitting on the cladding can be significant. This paper attempts to answer this question by using computational fluid dynamics techniques to obtain the pressure due to raindrops impinging on building faces.

2 STUDY OF WIND-DRIVEN RAIN

2.1 Background

Wind-driven rain (w.d.r.) is a topic that has long been investigated. In the early days, observations of rain blown by wind in the open was carried out by Hoppestad [1]. More recently w.d.r. intensity on building faces was investigated. In the 60’s field measurement of wind-driven rain on a building was carried out by Lacy[2][3]. In the 70’s Rodgers et. al.[4] studied w.d.r. on a building with a semi-analytical approach using wind tunnel testing results. In the late 80’s a fully analytical approach using numerical solutions of the computational fluid dynamic method was developed by Choi[5] and this method is used in the present study. Results of studies using this method has been compared with on-site measurement (Blocken & Carmeliet [6]) and experiment (Hangan [7]). Although there are differences between the various studies, they confirm the trend of variation predicted by the method.

2.2 Calculation of w.d.r.

The study of wind-driven rain around a building and the raindrops hitting on a building face can be divided into five steps.

1. Wind flow pattern around the building is computed to obtain the velocity vectors in the flow domain.
2. Raindrop trajectories moving towards and around the building are calculated for drops of various diameters; velocity normal to the building face at impact is also obtained.
3. Wind-driven rain intensities hitting different parts of the building face are then calculated for raindrops of a rainstorm.
4. The amount of rain water per unit volume of air during a storm of certain intensity together with the drop size distribution are needed for the estimation of the mass of rain water, and
5. The average cladding pressure due to w.d.r. is calculated from the change of momentum of the raindrop; the total contribution is obtained by integrating drops of all sizes.

Step 1: Wind flow pattern around the building
Wind flow pattern around a building is computed using the computational fluid dynamics method. A finite volume numerical scheme is used to solve the turbulent flow k-ε model.
where \( U_i \) is the \( X_i \) direction wind velocity; \( P \) is the pressure; \( \rho \) is the air density and \( \nu_t = C_\mu k^2/\epsilon \) is the turbulence viscosity. Value of other parameters are \( \sigma_1 = 1.0, \sigma_2 = 1.3, C_1 = 1.44, \)
\( C_2 = 1.92, \) and \( C_\mu = 0.09. \) Velocity vectors over the flow domain obtained from solving the above set of equations are used in the next phase of calculation.

Step 2: Raindrop trajectory
A raindrop moving through the air is acted upon by two forces – its self weight and the drag force by the surrounding moving air on the raindrop. The following are the equations of motion in the along-wind (\( x \)), cross-wind (\( z \)) and vertical (\( y \)) directions.

\[
\frac{dU_i}{dt} + dU_j dX_j = -\frac{d}{dt} \left( \frac{P}{\rho} + \frac{2}{3} k \right) + \frac{d}{dX_j} \left[ \nu_t \left( \frac{dU_i}{dX_j} + \frac{dU_j}{dX_i} \right) \right]
\]

\[
\frac{dk}{dt} + dU_i dX_j = \frac{d}{dX_j} \left( \nu_t \frac{dk}{dX_j} \right) + \nu_s - \epsilon
\]

\[
\frac{d\rho}{dt} + d\rho U_j dX_j = 0
\]

\[
s = \frac{dU_i}{dX_j} + \frac{dU_j}{dX_i} \frac{dU_i}{dX_i}
\]

Step 3: Wind-driven rain intensity
To calculate the intensity of wind-driven rain impinging onto the building face, raindrops (radius \( r \)) are generated at a regular spacing with known intensity, \( I_r \), at a distance far upstream of the building. Computing the trajectories of the raindrops, the locations of impact of the drops on the building face can be determined. Thus, the ratio of the intensity of the raindrops
(radius r) landing on certain location on the building face to the intensity Ir is equal to the number of raindrops per unit area landing on the location to the number of raindrops per unit horizontal area being generated. This ratio is termed the local effect factor, LEF(r), which is a function of the drop radius.

Step 4: Amount of rain water per unit volume of wind & drop size distribution
The overall effect of wind-driven rain due to a rainstorm is the overall combined contributions from raindrops of all sizes. The amount of raindrop of one size in a storm is different from those of other sizes; knowledge on the proportion of raindrops of different sizes in a storm is required. Studies of drop size distribution of rainfall have been carried out in many countries (Laws & Parsons [8]; Mualem & Assouline [9]). In the present study, the result of Best[10] who investigated rainfalls in USA, Canada and UK, is used. His study indicated that drop size distribution of raindrops can be expressed by the following equation

\[
F = 1 - \exp\left(-\frac{x}{a}\right)^n
\]

where 
\[a = A I^p\]
\[W = C I^f\]
F = fraction of liquid water in the air with drop diameter less than x (mm)
I = rainfall intensity (mm/hr)
W(I) = amount of liquid water per unit volume of air (mm³/m³)
A, C, p, r and n are constants with values 1.30, 67, 0.232, 0.846 and 2.25 respectively.

The study of Best also gives the amount of rain water per unit volume of air; thus, together with the drop size distribution, the amount of rain water of certain drop diameter per unit volume of air can be calculated. As both values are function of rainfall intensity (I), the result is also a function of I.

Step 5: Cladding pressure due to wind-driven rain
As the raindrops hit on the building face, forces will be generated due to the change of momentum. The average pressure on the cladding due to drop size r will be the force per unit area on the cladding due to raindrops of size r. The overall wind-driven rain pressure on the building face due to a rain storm is the overall combined contributions from raindrops of all sizes which is the sum of the contributions from each drop size weighted by the distribution probability. The pressure due to wind-driven rain is expressed in terms of the dynamic wind pressure, q, as a pressure coefficient Cp(I)wdr and is derived as follows:

\[
\text{Mass of rain water hitting on a horizontal surface} = \int \rho W(I) f(r) V(r)_{term} \, dr \\
\text{Mass of rain water hitting on building face} = \int \rho W(I) f(r) V(r)_{term} \text{LEF}(r) \, dr \\
\text{Cp(I)wdr} = \frac{1}{q} \int \rho W(I) f(r) V(r)_{term} \text{LEF}(r) U(r)_{wdr} \, dr
\]
Where $\rho$ is the water density; $W(I)$ is the volume of rain water per unit volume of air at rainfall intensity $I$; $f(r)$ is the probability density of drop size distribution; $LEF(r)$ is the w.d.r. local effect factor and $U(r)_{wdr}$ is the raindrop velocity normal to the building face at impact, and 

$q=\frac{1}{2}\rho_{air}V_{roof}^2$ is the dynamic wind pressure at roof height.

$V(r)_{term}$ is the raindrop terminal velocity, i.e. the constant vertical speed of the raindrop attained after free falling for a considerable distance. It is a function of the size of the drop. Experimental studies carried by Gunn and Kinzer[11] gave the following expression with units in mm and mm/s:

$$V(r)_{term} = 9500 \left( 1 - \exp \left[ - \left( \frac{2r}{1.77} \right)^{1.147} \right] \right) \quad (4d)$$

3 RESULTS OF STUDY

Studies were carried out using the method as outlined above on rectangular buildings of different height to width ratios. Velocity vectors in the x, y and z directions were obtained in the 3-dimensional domain using the $k-\varepsilon$ turbulent flow model. A sample plot showing the velocity vectors on a vertical plane along the centre line of the building is shown in Figure 1a; Figure 1b shows a plot on the horizontal plane at mid-height of the building. As expected, high wind speed sweeping around the side corners and top edge of the building is observed. In Figure 1a, immediately in front of the building the wind speed became very small and oriented in the vertical direction. These will have significant effect on the raindrop as they move close to the building.

Figure 1a  Velocity vector along a vertical plane
With the wind velocity components, $U$, $V$, $W$ obtained in Step 1, raindrop trajectories were solved using equation 2. The two forces that acted on the raindrop were the wind drag on the raindrop and the weight of the drop. The effect of wind drag relative to the gravitational pull was stronger on smaller raindrops than on larger raindrops. Therefore smaller raindrops tended to move with the wind; whereas larger raindrops tended to fall down. Figure 2a shows the trajectory of the 0.5mm diameter raindrop along with the wind speed vectors. The raindrop can be seen to move closely along the wind vector direction. Figure 2b shows trajectories of 5.0mm diameter raindrops. The raindrop was less affected by the wind drag and the vertical velocity component of the raindrop was relatively much larger.
In the horizontal direction, raindrops being sweep around the side corners of a building can be seen in the plan view of the trajectories. The effect was much stronger for smaller diameter raindrops than larger raindrops as shown in Figures 3a and 3b respectively.
To better visualize the movement of the raindrops around the building, Figures 4a and 4b shows the perspective views of the trajectories of the two sizes of raindrops.

![Figure 4a Perspective view of trajectories for 0.5mm raindrop](image)

![Figure 4b Perspective view of trajectories for 5.0mm raindrop](image)

The pattern of the trajectories of the raindrops was the result of the interaction between wind, rain and building. The shape of the building directly affected the blockage effect and hence on the raindrop trajectory. The trajectories around a narrower building which produced smaller blockage effect are shown in Figure 5 for 0.5mm diameter raindrop.

Wind speed plays a major role in the wind-driven rain phenomenon. The trajectories are obviously strongly affected by the wind speed. For a higher wind speed the horizontal velocity component of the raindrop are larger. Thus, the trajectories become more horizontal, and around building corners, the phenomena of raindrop being sweep around are stronger.
From the raindrop trajectories, it can be seen that the raindrops slowed down as they moved closer to the front face of the building. That means the velocity component of the raindrop normal to the building face became smaller. This effect was stronger for smaller raindrops than larger raindrops. The momentum of the larger raindrop moved it along its path towards the building face. The slow down effect was also stronger around the central and lower portion of the building face.

The horizontal speed of the raindrop normal to the building face expressed as a ratio of the roof-height wind speed for three study cases (1) narrow building (H:W=4:1) $V_{\text{roof}} = 19.0\text{m/s}$, (2) narrow building (H:W=4:1) $V_{\text{roof}} = 12.6\text{m/s}$, (3) wide building (H:W=1:2) $V_{\text{roof}} = 12.6\text{m/s}$ are given on the left side of Figures 6, 7 and 8 respectively. The front face of the building is divided into 3 vertical strips and 4 vertical bands, i.e. 12 zones. The velocity ratios are given for the corner points of each zone. As the problem is symmetrical, values on half the building face are given.
From the figures, it can be seen that the speed of the raindrop normal to the building face ($U(r)_{wdr}$) for the larger raindrops at around the roof level attains roughly the roof height wind speed. At lower heights, there is significant reduction of the $U(r)_{wdr}$ due to the blockage effect of the building, especially over the central portion. The reduction is more severe for lower wind speed than higher wind speed. This reduction is much stronger for the smaller raindrops. As expected, for the same wind speed, the reduction of $U(r)_{wdr}$ due to blockage effect is stronger for wide building than narrow building.

The next step in the evaluation of the pressure on the building face due to w.d.r. was to obtain the intensity of w.d.r. impinging on the building face. At a distance far upstream of the building, raindrops (radius r) were generated at a regular spacing with known intensity, $I_r$. From the raindrop trajectories, the locations of impact of the drops on the building face were determined. Thus, the ratio of the intensity of the raindrops (radius r) landing on certain location on the building face to the intensity $I_r$ was equal to the number of raindrops per unit area landing on the location to the number of raindrops per unit horizontal area being generated. This ratio is termed the local effect factor, LEF(r), which is a function of the drop radius. Values of LEF(r) for the three cases are also shown on the right side of Figures 6, 7 and 8. The values given are the average value for the zone.
From the figures, it is observed that the LEF(r) for the higher wind speed is much larger, especially for the smaller raindrop. This is because the smaller raindrops moved along with the wind almost at the same speed as the wind; and when the wind speed was high, it was much higher than the raindrop terminal velocity. Thus the number of drops per unit time passing a vertical plane was much larger than those of the normal rain falling on a horizontal plane. For wider buildings, the LEF(r) values were smaller due to the stronger blockage effect. Typically, the central portion of the front face of a wider building received much less w.d.r. than the top and side zones especially for the smaller raindrops. For a narrower building, the w.d.r. intensity of the larger raindrops became more uniform; with the central portion only slightly less than the side zones.

Using Equation 1, the volume of rain water in the wind and with the drop size distribution, the mass of rain water of certain dropsize per unit volume of wind can be calculated. Together with the velocity ratio and LEF(r) values just obtained, equation 4 can be used to obtain the average cladding pressure due to w.d.r. As Equation 3 is a function of the rainfall intensity I, the pressure coefficient also varies with I. $C_{p(I)}^\text{wdr}$ at the zone corner points of a narrow building under $V_{\text{roof}} = 19.0\text{m/s}$ and for $I=100\text{mm/hr}$ and $200\text{mm/hr}$ are given in Figure 9.
It can be seen that even for a rainfall intensity of 200mm/hr, the average pressure due to w.d.r. hitting on the building face is highest only less than 1% of the dynamic wind pressure at the top corner of the building. Values for $V_{\text{roof}} = 12.6m/s$ are also shown and they are observed to be smaller. For the wide building since both $\text{LEF}(r)$ and $U(r)_{\text{wdr}}$ are both smaller than a narrow building, $C_p(I)_{\text{wdr}}$ values are much smaller.

### 3.1 Localized w.d.r. pressure for a shorter duration

The values of the pressure caused by wind-driven rain as presented in the above are averaged values on a large area of façade over an hour duration. Studies had been carried out to evaluate the effect of space and duration on w.d.r. intensity.

**Average over time:**

It is understood that rainfall intensity over a short duration can be very intense, much higher than the average value over a longer period. Study by Linsley [12] showed the following relationship between rainfall intensity and duration.

\[
\frac{\text{Intensity (duration } t)}{\text{Intensity (hour)}} = \left( \frac{3600}{t} \right)^{0.42}
\]

Using the relationship, the intensity say for a 1-minute duration rain is 5.58 times more intense than the one-hour rainfall.

**Average over space:**

Wind-driven rain intensity on a building face is highly non-uniform. From the figures in the earlier section, w.d.r. intensity on the front face of a building is higher close to the roof and near the side edges of the building. To better illustrate, Figure 10 shows the w.d.r. intensity contours (shown are the drop-size weighted average $\text{LEF}(r)$ values) on a building face.

![Figure 10 Contours of w.d.r. intensity (drop-size weighted average $\text{LEF}(r)$) on building face](image)

As can be seen, the value of the averaged intensity of wind-driven rain of a patch of area depends on the size and location of the area. Study by Choi[13] gave a linear relationship be-
between the zone w.d.r. intensity and the Log of the zone area; and for a narrow building it is given as follows

\[
\frac{\text{Intensity (zone)}}{\text{Intensity (whole face)}} = -1.0 = -0.423 \log \left(\frac{A_{\text{zone}}}{A_{\text{whole face}}}\right)
\]  

Using this relationship, the w.d.r. intensity on a cladding of 1.0m by 1.0m would be 1.44 times the intensity of a zone (1/12 of the building face) as those given in Figure 9.

Thus, the pressure due to wind-driven rain on a piece 1mx1m cladding located at the top-side corner of the front face over a duration of 1-minute would be 1.44x5.58, i.e. about 8 times the value given in Figure 9 (at the top side corner the value as given in Figure 9b for a narrow building with \(V_{\text{roof}} = 19.0\)m/s and \(I=200\)mm/hr is 0.0084) which results 0.067. That is the extra pressure due to w.d.r is 6.7 percent of the dynamic wind pressure.

3.2 Variation of w.d.r. pressure with wind speed

The values of the w.d.r. pressure presented as above are calculated for a specific wind speed, \(V_{\text{roof}} = 19.0\)m/s. Looking at equation 4c, \(Cp(I)_{\text{wdr}}\) varies with \(\text{LEF}(r)\) and \(U(r)_{\text{wdr}}\). Previous study by Choi[13] showed that the average (dropsize weighted) \(\text{LEF}(r)\) increases proportional to \((V_{\text{roof}})^{1.73}\). And \(U(r)_{\text{wdr}}\) varies almost linearly with \(V_{\text{roof}}\). With the dynamic wind pressure being a function of \((V_{\text{roof}})^2\), \(Cp(I)_{\text{wdr}}\) therefore would be proportional to \((V_{\text{roof}})^{0.73}\). That is the higher the wind speed, the higher the \(Cp(I)_{\text{wdr}}\).

4 CONCLUSIONS

A frame work for the calculation of the average cladding pressure due to w.d.r. hitting on building faces is proposed. This involves the calculation of raindrop trajectories as they are blown by the wind and impact onto the building face. The speed of the raindrop at impact and the intensity of the wind-driven rain on the building face are calculated. From the momentum equation, the average pressure on the cladding due to the wind-driven rain droplets hitting on the building face can be obtained.

In general it was observed that the speed of the raindrop hitting on the building face as well as the intensity of the w.d.r. varies a lot with the location of the cladding on the building face. The speed and the intensity are much higher close to the top edge and side edges of the front face of the building. This results a higher pressure due to w.d.r. near the top and side edges.

The present paper calculated the pressure due to w.d.r. for a 40m high by 10m wide building and for a roof height wind speed of 19m/s and 200mm/hr rainfall intensity. It was found that though, the average w.d.r. pressure (averaged over an hour and for a large patch of cladding) is very low – less than one percent of the dynamic wind pressure, the w.d.r. pressure over a shorter duration of 1-minute on a 1.0m square cladding can be an extra of 6 to 7 percent the dynamic wind pressure.
REFERENCES


