Curious Case of Fire Urban Environment CFD: Campus Valla

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I. INTRODUCTION

Rapid Urbanization has been influencing climate change, energy consumption, health, transport, etc [1]. Hence, studying and predicting the aero-thermal phenomena of the environment in urban areas have become important. Urban physics is the science and engineering of physical processes in urban areas with multi-floor buildings, parts, bridges, skyscrapers a s well, etc. It refers to the transfer of heat and mass in both indoor and outdoor environments. Immense research has been in progress to better understand pollution dispersion, fire safety, wind dynamics, and pedestrian comfort which are essential concerns to slow down the urban heat island effect [2].

This study addresses the fire safety aspect of urbanization at Linköping University (Campus Valla) using Computational Fluid Dynamics (CFD) which is a useful tool to predict the nature of the fluid flow for the above-mentioned scenario. This can also be achieved experimentally using miniature models in the wind tunnel test facility. However, the experimental costs are huge, and control over the boundary conditions is less. Therefore, limiting the scope of experimental setups which in turn promotes significant research in the CFD domain for resolving microscopic to macroscopic scales. This study emphasizes the CFD modeling of the smoke propagation in Campus Valla and the identification of potential safe zones and affected buildings.

II. METHODOLOGY

This section highlights the methodology followed with the utilization of a verified mesh model of Campus Valla. A verified mesh model implies a sufficiently large domain to prevent the influence of boundary conditions in the area of interest by accounting for blockage issues, good mesh resolution with prism inflation layers at walls to accommodate surface roughness parameters i.e. aerodynamics roughness length (z_o), along with several other considerations [1].

The verified computational grid consists of 20 million elements with 10 prism layers growing from a triangular surface mesh at the solid walls. The bulk mesh generated with the octree-hexacore method, 2 buffer layers, and bulk element sizing ranges from 0.75 m close to the fire source to 25 m in the far field. The first cell height is 2.5 cm, yielding $10 < y^+ < 50$ for an incoming wind velocity of 5 m/s measured at 2 m above the ground.

The fundamental basis is the wind data [3] analysis, Fig.2 in order to identify scenarios for wind speed and direction. This study has focused on the months of October-November and the time slot of 1200-1700 hrs on the campus. based on the windrose, 5 cases are selected as mentioned in Table I which are discussed in the following sections.

The simulations are conducted in Ansys Fluent (V2022 R2) and performed on the high-performance computing (HPC) cluster Sigma at NSC (National Supercomputer Centre). A pressure-based steady-state RANS approach is used for the study with $k - \epsilon$ realizable turbulence model suitable for moderate-high speed flows. The enhanced wall treatment is incorporated to estimate boundary layer influences. The ground and wall boundaries are initialized with the no-slip conditions. Two boundaries (North and East) are assigned with pressure outlet conditions and two with inlet velocity (West-South) conditions, Fig. 1. At the velocity inlet, the velocity profile is applied to account for Atmospheric Boundary Layer [4] and surface roughness constant (z_o) Eq. 1 [4]. The components of the velocity profile are based on the wind directions. For fire/smoke sources, a passive scalar is used with the intensity of 1 i.e. smoke presence is denoted by 1 and absence by 0.

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The fire source is placed in front B5 as a patch cutout on the ground mesh with an upwards smoke velocity of 2 m/s, Fig. 1. The coupled solver is used for pressure and velocity coupling with a second-order discretization scheme for pressure and momentum, whereas the first-order for k and ϵ. The residual convergence criteria of $1e^{-4}$ were achieved as recommended in [1] with hybrid initialization of the solver.

$$V(z) = \frac{k * V_o}{ln\frac{z_r}{z_o}} * \frac{ln\frac{z}{z_o}}{k} \tag{1}$$

where, k = Von Karman constant, z = vertical height, z_o = 0.5 = aerodynamics roughness length [1] [4] because the campus valla is majorly surrounded by mixed farm fields, open grasslands, forest and scattered buildings which have comparatively lower height than B5, $z_r = \frac{2}{3}$*B5 (height), V_o = wind speed magnitude.

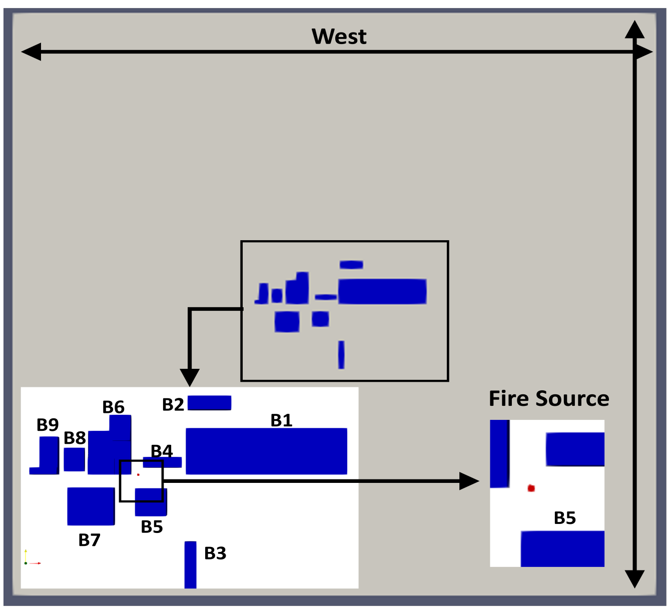

Fig. 1: Domain size with direction, buildings and fire-source mapping

III. RESULTS & DISCUSSION

The wind data analysis results are shown in Fig. 2, implying a high probability of wind direction from 210° to 230° i.e. from south-west to north-east and with the speeds in the range [0-15] m/s. The probability of the occurrence of each case is estimated using conditional probability, [5] Table. I). The highest probability is for Case2 followed by Case5 and Case1, whereas case3 is an outlier.

Table. I shows the buildings on campus Valla that are affected by the smoke. For all the cases, buildings [B2, B8, B9] are not affected by the smoke. For moderate (case5) and high (case3) velocity with 210° wind directions, B7 is only affected on the north face implying that the strong south component of the wind prevents smoke propagation towards the southern buildings. Also, the narrow stream between B7 and B6-B8 gives rise to high velocity which promotes the upward movement of smoke.

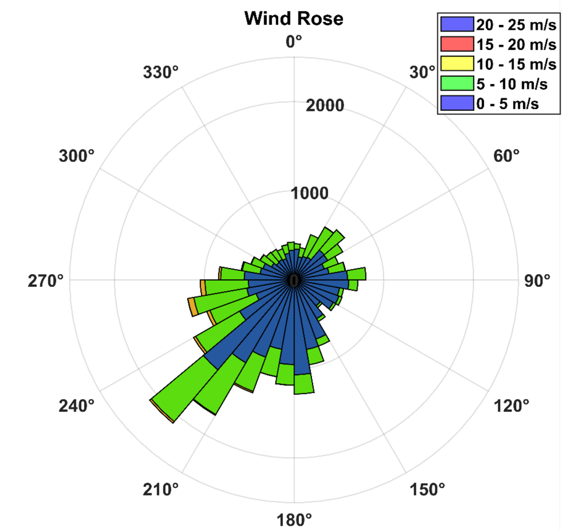

Fig. 2: Wind rose for analyzed wind data for October and November months since 1st Jan 2000 [3]

TABLE I: Affected building matrix

Columns	**Case1**	**Case2**	**Case3**	**Case4**	**Case5**
Speed m/s	4.09	4.45	12.33	1	4.11
Direction	220°	230°	210°	230°	210°
Probability	24.8	35.4	0.001	9.2	30.6
B1	1	1	1	1	1
B2	0	0	0	0	0
B3	1	1	1	1	1
B4	1	1	1	1	1
B5	1	1	1	1	1
B6	1	1	1	1	1
B7	1	1	0	1	0
B8	0	0	0	0	0
B9	0	0	0	0	0

Fig. 3 shows the 3D view of smoke propagation for Case2 towards North and East directions. The elevation of smoke covers the north face of B5 (39 m) and entirely covers B3. The eastern faces of B4 and B1 are blocked by the smoke which completely cut off the north passage. The southern and eastern faces of B5 are covered by smoke at the ground level. Due to the west wind component, the smoke affects B7 as well on the northern side which again due to the open inflow from the south directs the smoke towards B5 and B3.

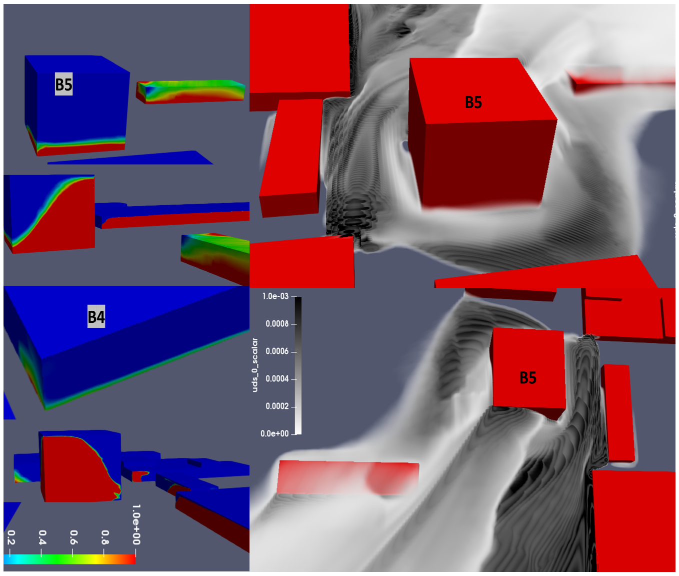

Fig. 3: Most Probable fire-smoke case (Case2)

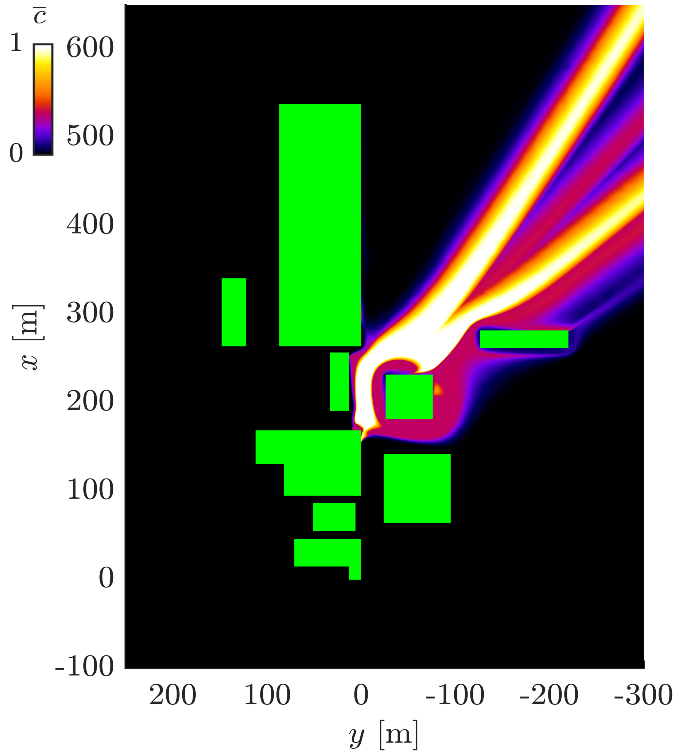

Fig. 4: Normalized weighted smoke concentration for 5 cases (z = $2m$)

An interesting way to visualize all five cases is to create a weighted average contour of the smoke scalar, Fig 4. The contour is created on a z-plane which is 2 m above the ground which helps in identifying the smoke concentration through which the crowd control should be performed in similar scenarios. The contour shows similar results as presented and discussed above where B3, B4, and B5 are significantly affected by the smoke. Small smoke concentrations are also observed to affects some sides of B1, B4, B6, and B7. The long and narrow passage in the north-south direction gives rise to high speed and low pressure resulting in smoke propagation to far north due to high speed and the re-filling of the smoke in between west face of B3 and east face of B1 due to low concentration 3.

IV. LIMITATIONS

A major constraint of the study is availability of validation data, hence no validation is presented. The wind direction is dominated by south-west with highly probably cases (1, 2, 5) at 4-5 m/s which restricts the smoke propagation towards west (beyond B4), Fig. 4. However, the low concentration smoke around B5 is due to the reversal after hitting B5 which then propagates towards north and south, and curls around B5. The model selection (RKE) is based on the $R_e = 3e^5$ implies turbulent flow and influence of building walls on the smoke propagation becomes important.

V. CONCLUSION

Based on the present study of fire/smoke propagation in an urban layout like campus Valla following conclusions are made:

- The west and south regions of campus Valla are the go-to safe zones for southwest wind in case of a fire breakout in front of B5.
- B2, B8, and B9 are least affected by the smoke and hence are good for crowd control activities.
- B3 and B5 are the most affected with all 4 sides affected with smoke.
- B1, B4, B6 and B7 affect with lower concentration of smoke of 1-2 sides and clear exits are available on un-affected sides.

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