

A numerical study of unsteady flow in a novel downburst simulator

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SUMMARY

In this study, we propose a novel downburst simulator and validate it numerically by comparison with available experimental and field data. This simulator features a tunnel shape with a rectangular cross-section, dividing part of its fetch length into upper and lower sections by a flow divider. By introducing variable inflow and/or outflow to the two sections, respectively, a downburst-like flow can be generated. The downburst location and wind profile can be controlled by adjusting the divider height, inflow and outflow conditions, enabling the generation of translating downbursts with different characteristics. In this study, we demonstrate that the proposed simulator successfully reproduces transient behaviour, nose-shaped wind profiles, and wind speed time series near ground for targeted translating downburst events, e.g., the downburst on 1 August 1983 at Andrews Air Force Base (AAFB).

Keywords: *translating downburst, transient flow simulator, computational fluid dynamics, non-synoptic wind*

1. INTRODUCTION

Downbursts can generate instantaneous wind speeds of up to 70 m/s near the ground (Fujita, 1985), causing significant danger to structures. The wind speed profile of downburst outflow differs from conventional boundary layer winds: horizontal wind speed peaks near the ground surface and decrease with height (Wood et al., 2001). Consequently, standard wind engineering practices based on boundary layer winds may not be applicable.

Translating downbursts, where the translating outflow is the superposition of the diverging wind and the storm's motion, are the most dangerous type, like the well-known AAFB microburst. The motion of downburst causes strong non-stationarity in wind speed and direction: (1) a rapid increase in wind speed during the touchdown; (2) a reversal of wind direction; (3) the occurrence of two distinct wind speed peaks.

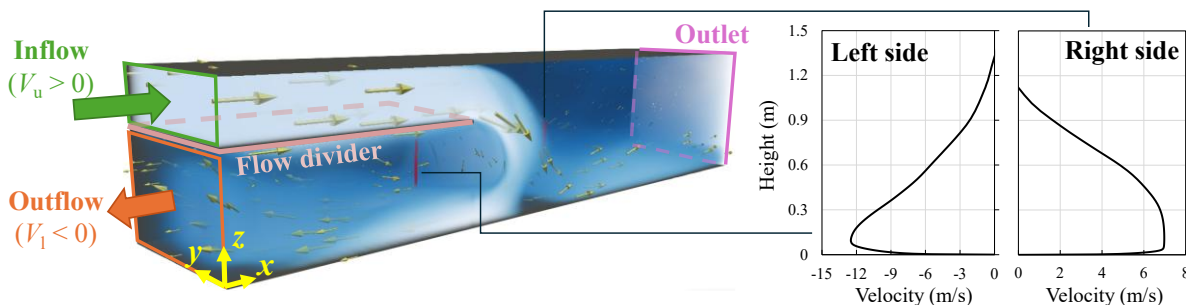


Figure 1: The transient flow simulator for downburst simulation (Size: x dir. 15 m, y dir. 3m, z dir. 3m).

Existing simulators for translating downbursts are primarily impinging jets, including small-scale devices, such as the moving jet by Chay and Letchford, (2002) and large-scale facilities like WindEEE dome (Junayed et al., 2019), which is capable of generating downburst-like winds. The former is limited by its small scale, while the latter is costly to construct, making them difficult to meet the demand for downburst research.

2. METHODS

This paper proposes a tunnel-shaped downburst simulator with a rectangular cross-section, called Transient Flow Simulator (TFS), as shown in Figure 1. A flow divider is set on the inlet side, dividing part of the fetch length into upper and lower sections. By applying an inflow and an outflow respectively at the sections, a downward flow can be generated that forms diverging ground flows.

This mechanism produces characteristic nose-shaped wind profiles on opposite sides of the stagnation point, as illustrated in Figure 1 for a flow ratio of 0.5 between the upper and lower sections. Guo (2022) has also confirmed the capacity of generating downburst-like wind profile using a small-scale TFS facility. Furthermore, preliminary parametric investigations reveal that the location and outflow characteristics can be controlled by modifying parameters, including flow divider height, flow ratio, and inflow profile. The inflow velocity is defined to be distributed linearly along height and depending on the gradient, the inflow profile can be upward-sloping, uniform, and downward-sloping.

In this study, we investigate numerically a three-phase control strategy to generate translating TFS-downbursts that mimic the dynamic behavior of real events, as outlined in Figure 2: **Phase A** – Maintain a constant flow ratio and a downward-sloping inflow profile, while increasing wind speed to form the touchdown; **Phase B** – Change the inflow profile to upward-sloping and reduce the flow ratio, resulting in TFS-downburst translation; **Phase C** – Reduce both inflow and outflow to weaken the TFS-downburst, resulting in a wind speed drop during the dissipation.

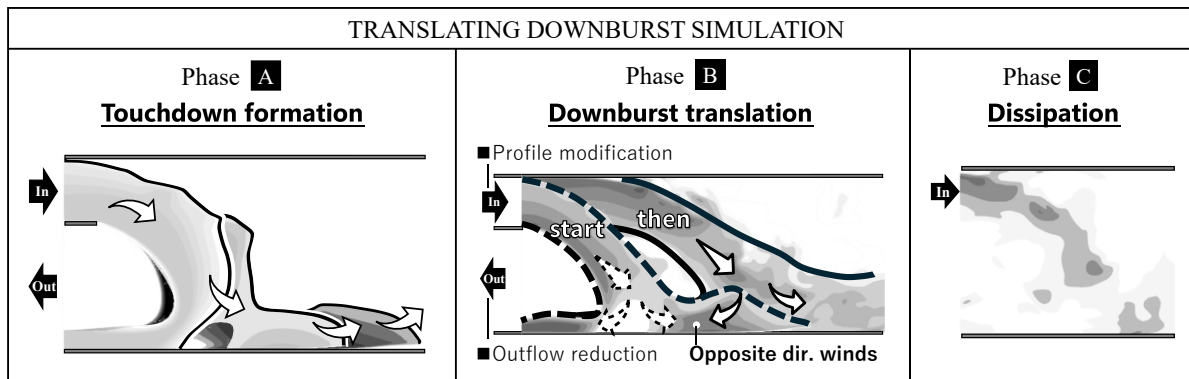


Figure 2: Translating TFS-downburst simulation.

Large Eddy Simulation (LES) was conducted using OpenFOAM ESI v2306. Walls were defined to be no-slip, including the 5-m-long flow divider at 2/3 of the TFS height. Moreover, velocity boundaries were defined using codedFixedValue function and described as functions of time and height. The solver was pimpleFOAM and the time step size was 0.0001 s.

3. RESULTS

Figure 3 depicts the normalized wind speed and direction results (blue line) at the measurement point ($x = 8.0$ m, $z = 0.05$ m), alongside anemometer measurements (black dashed line, circles) from the AAFB microburst (Fujita, 1985). The wind direction has been transformed such that the direction at maximum wind speed is aligned to 0° . The velocity distribution from time I to III depict the touchdown process where the downburst tilts rightward, contacts the ground, and forms a burst front, presenting a realistic transient behavior, and the wind speed increases rapidly to its maximum when the burst front passes through. At time IV, the TFS-downburst is passing above the measurement location, undergoing a bifurcation of air flow and a 180° shift in wind direction. At time V, the second peak occurs after the TFS-downburst passes. Overall, the normalized wind speed and direction demonstrated excellent consistency with the anemometer measurements.

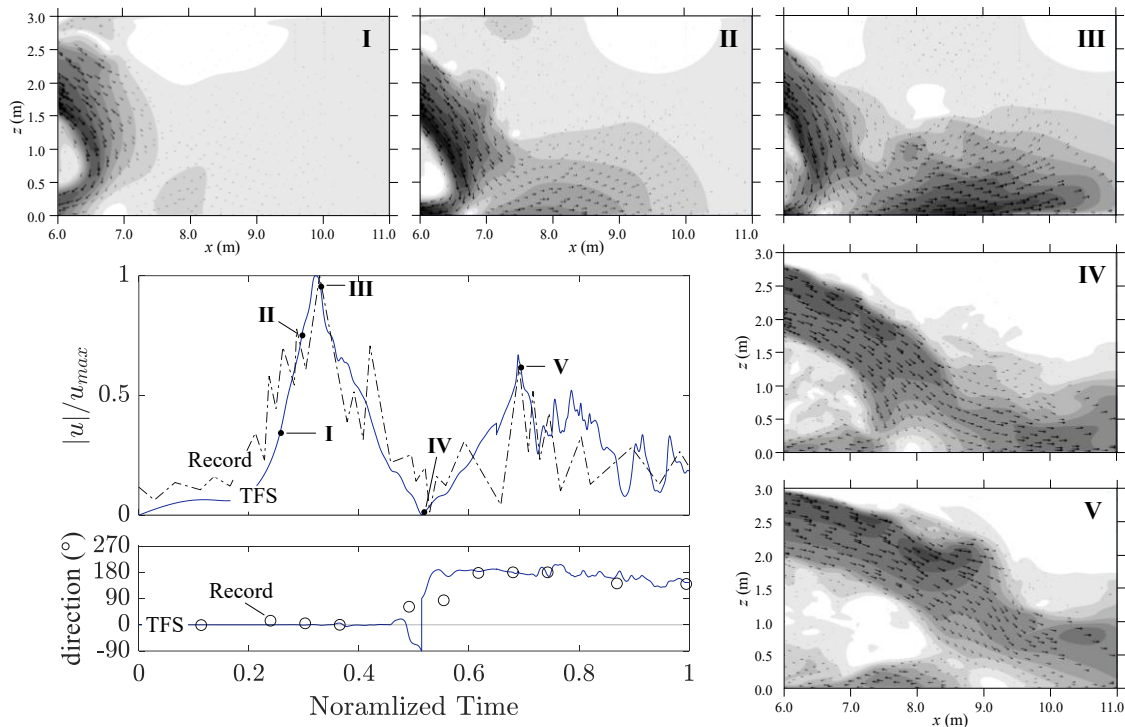


Figure 3: Wind speed and direction time series and velocity field during the translating TFS-downburst.

Figure 4 shows wind speed profiles at various time instances. At time III and V, strongest winds by translating outflow and trailing outflow, respectively, occurs near the ground, showing the vertical distribution characteristics of downburst winds. At time IV, near-ground wind speeds are close to 0, due to the existence of the stagnation under the TFS-downburst. Since surface roughness effects were ignored, maximum wind speeds are very close to the ground in this case, which can be adjusted by introducing greater roughness.

4. DISCUSSION

The proposed simulator adopts the test section configuration of conventional boundary layer wind tunnels, which allows the simulator to be modified from existing facilities. Wind tunnel tests can be conducted with a reasonable scale in such a simulator. Considering that the outflow profile

shape is adjustable in TFS, the height at 50% of the maximum wind speed, i.e., $z_{0.5\max}$, can be used as the characteristic length. Given the typical maximum wind speed height $z_{\max} = 50\text{--}100$ m observed in field measurements, and the ratio $z_{0.5\max}/z_{\max} = 0.22$ (Oseguera and Bowles, 1988), the estimated depth of downburst outflow is about 300 m. Meanwhile in our case (Figure 4), $z_{0.5\max}$ is evaluated as 0.75 m at the instant of maximum wind speed, yielding a corresponding scale of 1:400—an ideal scale for wind tunnel testing.

Further validation of TFS-Downburst under experimental conditions is still required. A potential approach would be designing a small-scale model with fan arrays to control inlet velocities, and visualizing TFS-Downburst using tracers to observe its morphology and translating behavior.

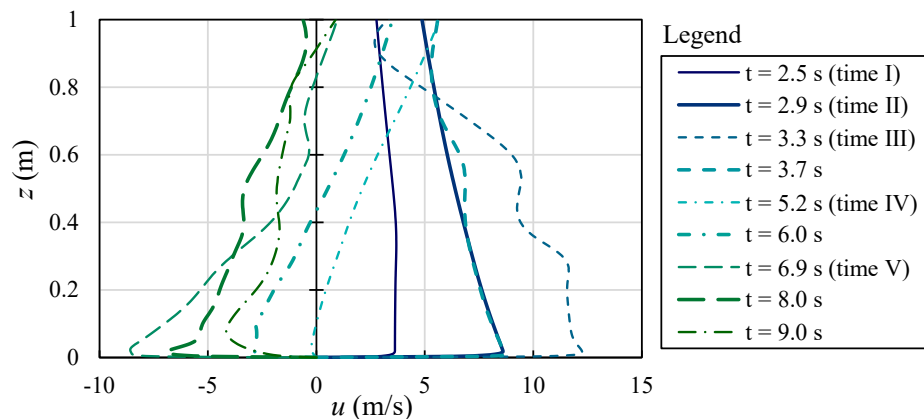


Figure 4: Wind speed profiles at various time instances during the translating TFS-downburst (at $x = 8$ m).

5. CONCLUSIONS

This paper proposes a novel downburst simulator. Numerical simulation results show that the simulator successfully reproduces transient behaviour, nose-shaped wind profiles, and wind speed/direction time series near ground for the AAFB microburst event, demonstrating its capacity for downburst-like wind generation.

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