pressure distribution on the middle cylinders from each column is given. In addition to that, the corresponding drag and lift force, frequency analysis of velocity signals and auto-correlations of streamwise and cross-wise velocities in the spanwise direction, which complement the existing experimental measurements, are reported. Finally, conclusions are drawn.

2 Computational methodology

2.1 Formulation of a dynamic Smagorinsky model

The governing equations for LES are obtained by spatially filtering the Navier-Stokes equations. In this process, the eddies that are smaller than the filter size used in the simulations are filtered out. Hence, the resulting filtered equations govern the dynamics of large eddies in turbulent flows. A spatially filtered variable that is denoted by an overbar is defined using a convolution product (see [30])

$$\overline{\phi}(\mathbf{x},t) = \int_{\mathcal{D}} \phi(\mathbf{y},t) G(\mathbf{x},\mathbf{y}) d\mathbf{y} \tag{1}$$

where $\mathcal{D}$ denotes the computational domain, and G the filter function that determines the scale of the resolved eddies.

In the current study, the finite-volume discretization employed itself provides the filtering operation as

$$\overline{\phi}(\mathbf{x},t) = \frac{1}{V} \int_{\mathcal{D}} \phi(\mathbf{y},t) d\mathbf{y}, \quad \mathbf{y} \in \mathcal{V} \tag{2}$$

where V denotes the volume of a computational cell. Hence, the implied filter function, $G(\mathbf{x},\mathbf{y})$ in eq.(2), is a top-hat filter given by

$$G(\mathbf{x},\mathbf{y}) = \begin{cases} 1/V & \text{for } |\mathbf{x}-\mathbf{y}| \in \mathcal{V} \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

Filtering the continuity and Navier-Stokes equations, the governing equations for resolved scales in LES are obtained

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0 \tag{4}$$