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The Influence of Computational Parameterization on Mean Flow and Turbulence Statistic in 2D Idealized Street Canyon: Computational Domain

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ABSTRACT

The use of Computational Fluid Dynamics (CFD) as a research tool has been utilized in many ways to predict the turbulent flow nature and pollution dispersion in an urban environment such as street canyon. Apart from the advance advantages offered by this method, some problems can be arising on respect to accurate prediction of data and uncertainties of the assumption that are made in numerical modelling. The execution and evaluation of the CFD studies need to undergo validation and generic sensitivity analyses to minimize the computational error and have an accurate prediction of data. This study performs a series of large eddy simulation (LES) to investigate the flow fields within and above a two-dimensional idealized street canyon with a unity aspect ratio (ratio of street width, W to building height, H). The effect of domain size on turbulent statistics is evaluated through the implementation of three different domain sizes i.e. varied streamwise lengths with fixed spanwise length and vertical height for different grid resolution (coarse, medium and fine). Comparison with the available experimental results shown a good agreement for mean velocity profiles. However, current LES underestimates the higher-order turbulent statistics. For the mean flow, the LES predicts the streamwise flow in the upper part and reversed flow in the lower part of the canyon, indicating the well-known flow regime of skimming flow. The value of mean velocities for all cases of the run have almost matching profile inside and above the canyon. For all cases, the maximum values of standard deviation in the streamwise and vertical directions are located approximately near the roof-level windward wall represent the occurrence of velocities fluctuation. In contrast, the Reynold shear stress for all cases shows some discrepancy where the peaked of turbulence intensity near the roof height is not smoothly captured in the current LES. Study shows that the LES cannot properly simulate those statistics accurately when the streamwise domain is limited to 10H even with the increasing of grid resolution sizes. Nevertheless, these results are expected to provide additional information relevant to uncertainty estimation upon execution of computational fluid dynamics (CFD) simulation.

Keywords:
Street canyon; Wind tunnel; LES; Computational domain; Turbulence

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1. Introduction

The deterioration of air quality associated with road transport has been considered as a major environmental issue in urban areas. Studies have shown that short-term or long-term exposure to traffic-generated pollutants results in various adverse health problems [1]. The investigation of dispersion of atmospheric pollutants within a street canyon has been considered as an interesting area for the environmental research due to their wide range parameter that depends on many aspects such as meteorology and wind engineering, where it is still having a lot of potential to be explored.

With rapidly improving computer power, computational fluid dynamics (CFD) has become a popular tool to study air pollution in street canyons in the last decade [2]. According to Zhong *et al*., [3] CFD can provide a complete view of the distribution of flow and pollutant fields at high-resolution in both time and space, which other methods could not tackle this matter. It was found that the most comprehensive applications of CFD have been used was based on Reynolds averaged Navier-Stokes (RANS) equations and large-eddy simulation (LES).

RANS has been used to predict the flow and pollutant dispersion within street canyons at the earlier of studies by using two-dimensional steady-state Reynolds average Navier-Stokes two-equation k−ε turbulence model and their corresponding turbulence closure schemes [4]. Several previous RANs of street canyon flow have been reported; [5-13].

Recently, interest has risen in employing Large Eddy Simulation (LES) to address the shortcomings of RANS. LES have been considered more superior than the RANS technique due to their reliability and accuracy. The major advantages of LES are its capability of handling the unsteadiness and intermittency of the flow, as well as providing detailed information on the turbulence structure, which, however, cannot be obtained from the k − ε model [14]. The approach of LES generally models the time-dependent equations by solved it on a grid that is too coarse to capture the small scales of the flow that substantially reduced the computational demand. Meanwhile, the effects of the smaller eddies are then modelled [15].

Many modelling studies of the flow and turbulence structure in a street canyon have been conducted in previous years using the LES model. Liu and Barth [16] have modelled a three-dimensional street canyon using an LES model with unity building height-to-street-width aspect ratio to illustrate the flow structure and scalar transport. Cui *et al.,* [17] and Kikumoto and Ooka [18] also conducted a study of flow and turbulence characteristic by using LES in the street canyon with unity aspect ratio. Besides, Li *et al.,* [19] have applied an LES model to simulate the airflow and pollutant transport in the deep street canyons with different aspect ratio. Furthermore, previous LES studies not only looked at the generic idealized urban geometry but also conducted the simulation on various architectural and urban elements. Study by Mohamad *et al.,* [20] simulated a two-dimensional street canyon with various overhang lengths using LES.

Besides, studies in regards to LES analysis have been extended by looking on a different parameter other than focusing solely on the geometry aspect only. Li *et al.,* [21] have calculated some statistical average properties to further examine the pollutant distribution, retention time as well as the air exchange rate (ACH) and pollutant exchange rate (PCH) by using the LES analysis. Li *et al.,* [22] have explored the effects of ground heating on the wind and thermal environment and pollutant dispersion in urban areas. Meanwhile, Zhong *et al.,* [3] studied on the reactive pollutant instead of passive pollutant to represent the real situation of street canyon environmental when exposed to emission of vehicle. A list of studies has been published on flow structures and pollutant dispersion in street canyons using LES; [23-32].

Despite its widespread use, the accuracy and reliability of CFD modelling and the correct use of CFD results are found can be easily be compromised [33]. Franke [15] stated that the main objection of this issue is due to the availability of many physical and numerical parameters in the approach, which can be freely chosen by the user. Two types of parameters that act as sources of error in CFD result is physical modelling based on turbulence models and the applied boundary conditions, while the other govern by numerical simulation such as computational domain size, grid design and numerical iteration algorithm [34].

In many years, a lot of sensitivity tests and detailed verification and validation exercises have been conducted in comparative studies. The verification and validation of numerical modelling is designed to reduce programming error while sensitivity analysis found can be used to provide additional information relevant to uncertainty estimation. While many lessons have been learnt from those previous studies, it was noted that most of the studies are aimed at validation with a few general guidelines for the setup of the numerical model. A rigorous study of the effect and contribution of those error parameter on the accuracy of the flow and turbulent intensity statistics has not been fully attempted to the knowledge of the author. There is a high uncertainty which parameter of physical modelling and numerical simulation approximation that play a major role in contributing to predict the airflow and turbulence intensity correctly.

Therefore, the motivation for the overall of this study is to use LES to validate and statistically analyse the significant contribution of two parameters of numerical approximation; domain size and grid resolution, towards the accuracy of the simulation model for idealized urban street canyon environment. However, for this paper, the relation between the airflow and turbulence intensity structural, and their interactions both inside and above the street canyon will be studied first for various size of the computational domain. The domains selected are designed to be limited into three sizes with gradually increase in the streamwise length and different sizes of grid resolution, thus, it is expected to capture the accuracy of the data in such manner. The results should be expected to enrich the fundamental understanding, as the computed flow and turbulence are the prerequisite for the pollution dispersion simulation model and also increase the confidence in computational wind engineering aspect.

2. Methodology

2.1 Governing Equations

The continuity and momentum equations for steady incompressible are given as follows,

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

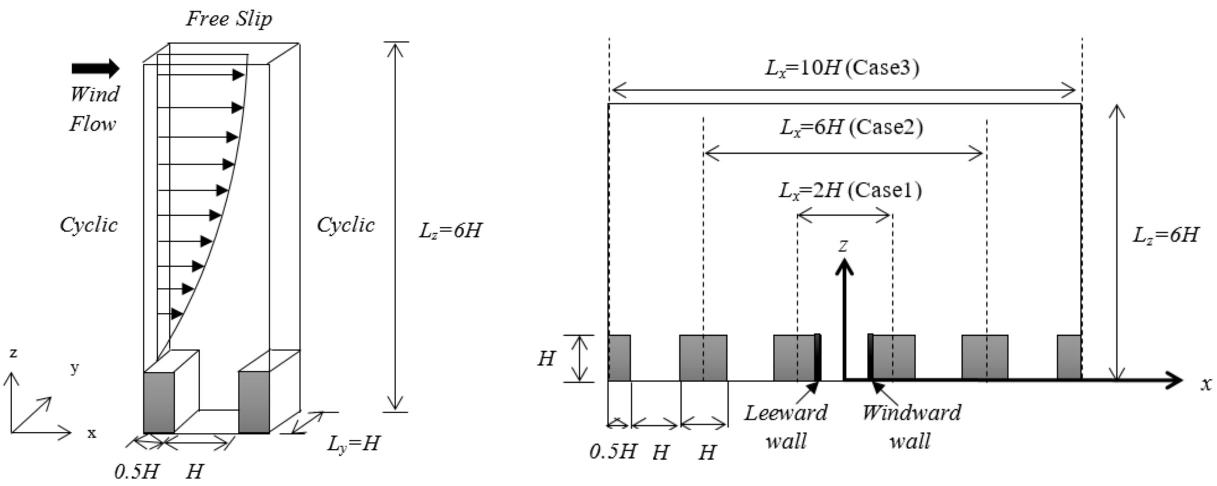
$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\upsilon \frac{\partial \bar{u}_i}{\partial x_j}\right) - \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where the overbar denotes the filtered value, u_i is the velocity vector and *P* is the pressure, υ is the fluid kinematic viscosity. τ_{ij} represents the subgrid-scale (SGS) Reynolds stress. These terms were modeled using standard Smagorinsky model with C_s constant of 0.12. The Reynolds number based on the block height (H=0.12m) and the average velocity at z/H= 2.0 (u_{ref}) is calculated from Eq. (3). All the simulations were carried out using the open-source CFD code OpenFOAM v2.3.1.

$$Re = \frac{uH}{\upsilon} \tag{3}$$

2.2 Simulation Domain

Three different computational domains are adopted in this study as shown in Figure 1. Each domain is characterised by the length in each direction in term of streamwise (L_x), spanwise (L_y) and vertical (L_z) directions. Case 1 is defined as 2H x H x 6H, 6H x H x 6H for Case 2 and 10H x H x 6H for Case 3. Case 1 with a grid size of H/8 is used for validation with the wind tunnel experiment by Michioka *et al.,* [36] as shown in Figure 1(a). Meanwhile, three runs are implemented to check the influence of domain size on the turbulence statistics (see Figure 1(b)) for coarse (H/8), medium (H/16) and fine grid (H/32) resolution define as G8C123, G16C123 and G32C123, respectively.



(a) (b)

Fig. 1. Schematic of the computational domain adopted in this study (a) Case 1 for validation purpose (b) Configurations of simulated urban street canyon for Case 1, Case 2 and Case 3

A uniform height (H = 0.12 m) of square arrays are arranged at the bottom surface corresponds with the domain size. As the aspect ratio of all simulations is unity, the number of the canyon is varied for each case as one for Case 1, three for Case 2, and five for the Case 3. The height of the domain was set to 6H as proposed by Franke *et al.,* [35] and the spanwise domain length was kept at H. The domain was discretized into a uniformly structured mesh with a grid size of H/8, H16 and H32 for each case of runs. The number of grids for each case is defined as $N_x \times N_y \times N_z$ represent the total number in streamwise, spanwise and vertical, respectively as depicted in Table 1.

To simulate infinitely repeated street canyons cyclic boundary conditions are imposed in the streamwise and spanwise directions. No-slip boundary conditions are imposed on the bottom surface and building surfaces, while free slip boundary conditions are applied on the velocity components at the top boundary, where the velocity normal to the boundary equals zero and the gradient of velocity parallel to the wall should be zero. The flow is driven by additional source term in the Navier-Stokes (NS) equations to ensure the averaged velocity over a cross-section is maintained at 2 m/s. The time step is set to 1.0 x 10^{-4} to ensure the mean Courant number is less than one. The sampling frequency of the data is 500Hz. The Reynolds number is range between 10000-12000 for all cases of simulations for this study.

Table 1
Computational domains and total grid

G8C123	Case 1	Case 2	Case 3
L_x/H	2	6	10
L_y/H	1	1	1
L_z/H	6	6	6
N_x	16	48	80
N_y	8	8	8
N_z	48	48	48
G16123			
L_x/H	2	6	10
L_y/H	1	1	1
L_z/H	6	6	6
N_x	32	96	160
N_y	16	16	16
N_z	96	96	96
G32C123			
L_x/H	2	6	10
L_y/H	1	1	1
L_z/H	6	6	6
N_x	64	192	320
N_y	32	32	32
N_z	192	192	192

3. Results

3.1 Model Validation

To validate the current model, the vertical profiles of the resolved-scale mean velocities, standard deviations and Reynold shear stress calculated by current LES are compared with those wind-tunnel results of Michioka *et al.,* [36] as shown in Figure 2. The height and the velocity are normalized by the building height H and reference velocity u_{ref} at a height of 2H, respectively.

The mean velocity profile (Figure 2(a)) shows generally good agreement with the wind tunnel results especially within the canyon (z/H<1) where the reversed flow has been predicted. However, at a higher elevation (1 < z/H > 1.3) current LES underpredict the velocity where the shear effect is dominant. Considering the profiles of current LES become smoother across the building height as predicted in the wind-tunnel experiment, it is acceptable that the current LES reproduces the mean flow field within and above the street canyon and the fully developed wind profiles have been sampled.

On the other hand, the streamwise-velocity standard deviation σ_u for the current LES are much smaller than those of the wind tunnel data experiment, as seen in Figure 2(b). It is maybe due to small domain size that might restrict the development of coherent structure as pointed out by Kanda *et al.,* [37]. This also reflect to Reynolds shear stress profile where the current LES is underpredict the peak at the building height as shown in Figure 2(c). Nevertheless, apart from the discrepancy, the shapes of the LES profiles are qualitatively similar to those obtained by the wind tunnel.

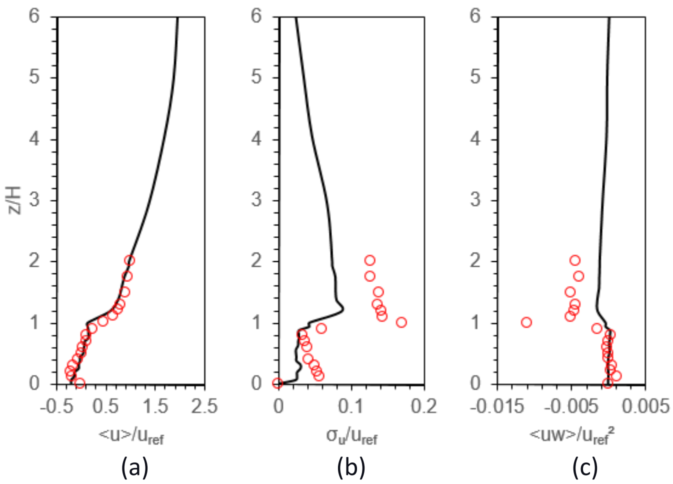


Fig. 2. Vertical distribution of the; (a) Streamwise mean velocity (b) Streamwise standard deviation and (c) Reynold shear stress at x/H=0. The solid line refers to the present simulation result, and the open circles refer to the data of the wind tunnel experiment (Michioka *et al.,* [36])

3.2 Flow and Turbulence Structure

Figure 3 shows the comparison of vertical distributions of the spatially averaged mean streamwise velocity for all domain sizes with coarse, medium and fine grid resolutions. All those runs produced very similar results where a noticeable velocity gradient is developed along the roof level as more extensive turbulent mixing occurs, representing the fully developed wind profiles have been sampled. The LES predicts the reversed flow in the lower part signifies the rotating primary vortex that present in the canyon. The averaged flow intensity inside the canyon does not significantly change regardless of the size of the computational domain and the mesh resolution use within this case of study.

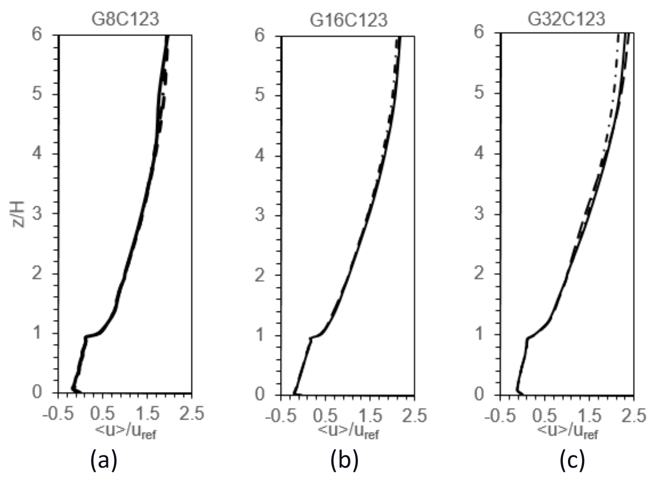


Fig. 3. Vertical distribution of the mean streamwise velocity for all cases of domain size with different grid resolution (coarse: G8C123, medium: G16C123 and fine: G32C123). The dash line refers to the: Case 1, solid line: Case 2 and dash-dot line: Case 3

Meanwhile, the vertical profiles of spatially averaged streamwise and vertical velocities fluctuations, σ_u and σ_w are depicted in Figures 4 and 5 respectively. Within the street canyon, the LES produce almost similar profile where the maximum σ_u and σ_w are initiated approximately right over the street canyons and building roofs for all the run cases (G8C123-G32C123). At the z/H=1, the intensities for each case of the domain are found to be different about 19% to 23% from coarse to fine grid resolutions. However, above the canyon, the LES underestimates the magnitude of σ_u and $\sigma_{w,}$ most noticeably for the coarse-resolution runs. In the comparison of the standard deviation, both σ_u and σ_w, results reveal that there is an increment of the value for the standard deviation due to the effect of grid resolution for each runs while no significant changing is predicted for different size of the computational domain.

As for Figure 6, the Reynolds shear stress obtained by the LES for runs G8C123-G32C123 shows an obvious discrepancy in results, for all cases of simulation. The LES cannot properly simulate those statistics since the typical well-known dogleg shape indicate a peak appears at the roof height, are not smoothly capture. At the lower part of the canyon (z/H≤1), the results are generally agreeing well with others for all cases of domain in each run of simulations. However, above the canyon approximately at z/H=1.5, the magnitude value of velocity fluctuation is gradually increased by about 70%, from coarse to fine-resolution. All the statistic for Case 1-3 for all runs has not significantly changing in respect to increasing and decreasing horizontal domain.

By comparing, it was indicating that increasing the domain size for different grid resolution (in this particular study) does not fully rectify the under-predicted turbulent statistics in the street canyon.

From Figures 3-6, the finding shows that the correlation among domain size for grid resolution (H/8, H/16 and H/32) does not significantly rectify the discrepancy of the turbulence statistic. Theoretical studied stated by Cui *et al.,* [17], mentioned that the correct prediction of temporally averaged fields still can be produced even if the higher moments are not perfectly predicted in LES. The findings also consistent with the previous study by Kanda *et al.*, [37], that mentioned the development of the coherent structures above the street canyon cannot be properly simulated in a small domain. This can justify the condition occur within this study where the mean velocities can be well reproduced in all varied domain sizes but underestimated the standard deviations and Reynold shear stress.

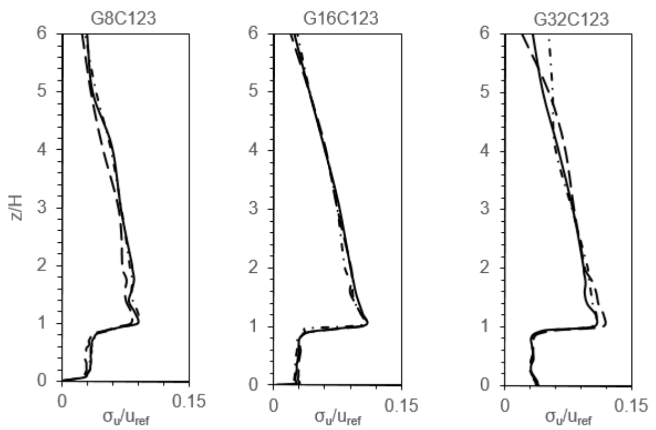


Fig. 4. Vertical distribution of the standard deviation of streamwise for all cases of domain size with different grid resolution (coarse: G8C123, medium: G16G123 and fine: G32C123). The dash line refers to the: Case 1, solid line: Case 2 and dash-dot line: Case 3

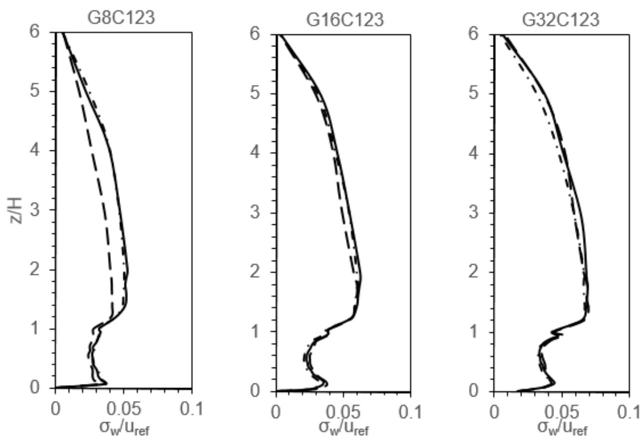


Fig. 5. Vertical distribution of the standard deviation of vertical velocity for all cases of domain size with different grid resolution (coarse: G8C123, medium: G16C123 and fine: G32C123). The dash line refers to the: Case 1, solid line: Case 2 and dash-dot line: Case 3

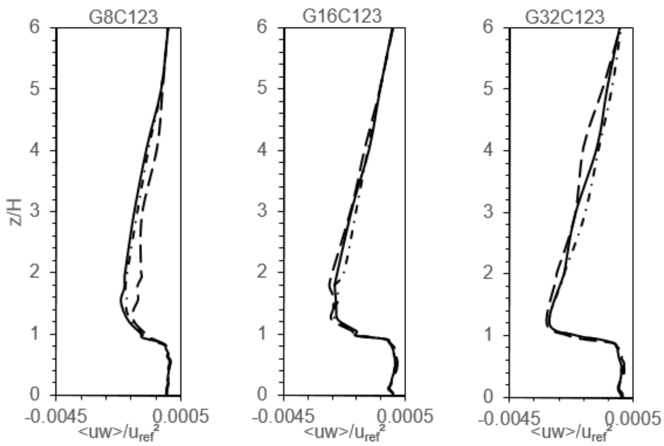


Fig. 6. Vertical distribution of the Reynold shear stress for all cases of domain size with different grid resolution (coarse: G8C123, medium: G16C123 and fine: G32C123). The dash line refers to the: Case 1, solid line: Case 2 and dash-dot line: Case 3

4. Conclusions

A large-eddy simulation (LES) model with a unity aspect ratio (AR=1) was modelled to investigate the flow features within and above the idealized two dimensional (2D) street canyons. A series of simulation consisting of three different sizes of the computational domain for different sizes of grid resolution has been conducted.

The results obtained show that the validation exercise demonstrated that the current LES model gives reliable mean velocity while comparing with the wind-tunnel result from the Michioka *et al.,* [36]. In contrast, the profile of the standard deviation of streamwise and the Reynold shear stress indicate some discrepancies resulted from the small domain use for the simulation case. It is believing due to the coherent structures that have developed above a canyon cannot be properly simulated in a small domain.

Meanwhile, in respect to the effect of domain size on the accuracy of the flow and turbulence structural statistic study, the average mean streamwise velocity can be produced in the current LES and have an almost similar result of profile regardless of the size of the domain for coarse, medium and fine grid resolutions. It is suggesting that the averaged wind fields are relatively less dependent on the size of the domain. Meanwhile, for the second moment of turbulence statistics, all the cases of simulation indicate only slightly increment of the magnitude with the increment of the domain sizes.

In contrast, the velocity fluctuation of Reynold shear stress is found to be sensitive to the parameter of the size of the computational domain. The data of Reynold shear stress for all cases are shows some discrepancy in the magnitude value and not reasonably being reproduced. The study shows that the LES implemented in limited computational domain size (which is less than ten times the canyon height) cannot properly reproduce the instantaneous turbulent structure that restricted by the streamwise domain size, as pointed by Kanda *et al.,* [37], even by increasing the sizes of grid resolution. Thus, the cause which is also believed to be the result of the insufficient resolution use for LES that as well adopts a limited domain size. Therefore, a more detailed analysis is required to examine the correlation among domain size and mesh resolution and their significant contribution to the accuracy of the numerical simulation aspect.

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