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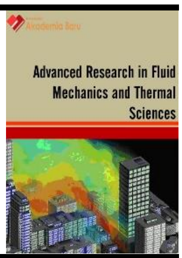

A CFD Study of Flow Around an Elevator Towards Potential Kinetic Energy Harvesting

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ABSTRACT

The regenerative drive and braking elevator technology capture the kinetic energy from the rope movement based on Faraday's law of electromagnetic induction, thus only applicable to the roped elevator system. The rope-less elevator is anticipated to be future predominant elevator type and can only transfer its kinetic energy via the airflow induced by its car movement, which can be evaluated via aerodynamic studies. However, past aerodynamic studies focus only on the effect of the induced airflow to energy and operational efficiency of the elevator. There are very limited studies on the use of the induced airflow for kinetic energy harvesting. Therefore, this study evaluates the induced flow in terms of air velocity, kinematic pressure, and turbulence, towards the potential kinetic energy harvesting pertaining to the possibility of wind power generation and electricity generation of the rope-less elevator system using CFD based approach through OpenFOAM software. Aerodynamics of the elevator system is simulated using symmetrical quarter three-dimensional elevator model, with parameters of car rated speed and shaft height. The results reveal the potential kinetic energy harvesting from the moving elevator car. Appropriate elevator speed and shaft height should be adjusted accordingly to get the optimum match with the longest time period for the car to run at its rated speed, to generate the most electricity.

1. Introduction

In recent years, there are more than seven billion elevator trips are made every single day in the world [1]. This contributes to the high elevator energy consumption of up to 2 to 40 % of the total high rise building energy consumption [2]. Elevator energy consumption greatly depends on elevator car and shaft characteristics, motor type, control system, ancillary system, as well as traffic [3]. Conventional elevator system is fully powered by the active energy system which use the electricity generated from the non-renewable energy source, for example, electricity from the electric grid. It is high energy consumptive.

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In order to overcome the high elevator energy consumption, modern regenerative elevator system has been introduced. It uses mainly the active energy supply and supplemented by the passive energy supply which is the electricity regenerated within the system itself, for example, from the kinetic energy of the motor shaft rotation. It saves 17 to 73.54% of energy compared to the conventional elevator [4–7]. Currently, the most common regenerative elevator system is traction type regenerative elevator system, which comprises of the regenerative drive and regenerative braking with motor that regulating the potential and kinetic energy produced via natural gravity pull and motor [2,8,9]. It works based on the Faraday's law of electromagnetic induction, which use the kinetic energy of the motor shaft rotated by the moving rope to induce the current, thus limited to roped elevator system [10-11]. Various studies have been carried out to develop elevator regenerative technology on roped elevator system, including hydraulic and traction elevators. Several studies were carried out on regenerative hydraulic technology [12–14]. The traction regenerative technology was studied in [15–17]. This regenerative elevator technology which only applicable on the roped elevator became an issue when rope-less elevator is emerging and predicted to be the predominant type in the future. The rope-less elevator system is a non-contact system, so the kinetic energy caused by the car motion can only be transferred through the induced moving air particles surrounding the car within the shaft, in the form of high speed airflow. Therefore, aerodynamic study of rope-less elevator system is needed to evaluate the potential kinetic energy harvesting from the airflow induced by the rope-less elevator car movement within the shaft.

The elevator energy efficiency can be achieved via aerodynamic study of elevator system using computational fluid dynamic (CFD) software or experimental approach such as wind tunnel experiment [18,19]. Most of the existing elevator aerodynamic studies focus on the effects of airflow induced by the moving elevator car to its safety in additional to the energy and operational efficiency such as speed and vibro-acoustic performance. However, very limited elevator aerodynamic studies emphasized on the use of the induced airflow, pertaining to potential kinetic energy harvesting from it. In earlier, Shi *et al.,* [20] studied only the two-dimensional (2D) forces, which were velocity and pressure in the elevator system, aiming for a better elevator system designation, to increase its operational and energy performance. However, the two-dimensional (2D) simulation may miss out some significant forces. Since the movement of the resultant air is in both lateral and vertical direction, Pierucci and Frederick [21] in the later study, started to do 3-dimenstional (3D) simulation. They focused on multidirectional force and wave surrounding the car to determine the vibro-acoustic factor in high speed elevator system. In the most studies, 3D symmetrical quarter model was used, and was proven to save computational cost without compensating the accuracy of results. Wang *et al.,* [22] studied on the effect of the distance between shaft wall and car wall on the aerodynamic performance of the elevator system. It was reported that the larger the distance, the smaller the blockage effect, thus the better its aerodynamic performance. Another study on roped elevator system using CFD was performed by Wu *et al.,* [23], using detailed fluid-structure interaction (FSI) technique to capture a more comprehensive multidirectional force and oscillation of the conveyance. Above mentioned studies aimed mainly to improve the operational performance and ride quality of the elevator system, without focusing on the potential kinetic energy harvesting within the elevator system.

Throughout the open literature, most of the computational fluid dynamic studies adopt ANSYS Fluent software due to its simplicity [24–27]. But recently, the utilisation of OpenFOAM software has emerged as computational fluid dynamic tool pertaining to elevator aerodynamic study [28,29]. For instance in a study by Singh *et al.,* [30], different turbulence models were used to capture different sizes eddies in order to obtain more accurate and comprehensive turbulence pattern passing the car based on CFD approach using OpenFOAM. Previous studies clearly simulated the aerodynamic flow and piston effects present in the elevator system with multiple cars [28,31]. Nonetheless, these studies did not focus on the potential kinetic energy produced from the aerodynamics (the behaviour and pattern of the airflow induced by the elevator car movement) of the moving elevator system.

Taking into account the above facts, this present study aims to investigate the aerodynamics of the moving elevator system towards the potential kinetic energy harvesting pertaining to the possibility of wind power generation and electricity generation of the rope-less elevator system. It is performed based on modelling and computational fluid dynamics simulation approaches, using OpenFOAM software. The present study evaluates the velocity, kinematic pressure, and turbulence of the induced flow of air, to determine the potential of kinetic energy harvesting, as well as the significant spots for the possibility of kinetic energy harvesting. Since there is very limited space within all elevator systems, the typical small-scale wind energy portable turbine is used as a reference for computational methods, the typical value of coefficient of wind turbine performance and swept area of blade are used [32,33]. It also presents the effect of the combination of elevator rated speed and the shaft height to the time period which the car is running at its rated speed and producing the maximum kinetic energy. Findings from this study could provide fundamental information prior to costly experimental investigations.

2. Methodology

2.1 Principles and Equations

The main principles which govern this study are conservation of mass and momentum, with fixed air density, dynamic viscosity and kinematic viscosity. Changing air velocity in three directions, U_x, U_y, U_z; pressure, p; turbulent kinetic energy, k; and dissipation rate of turbulent kinetic energy, epsilon are simulated.

The atmospheric pressure and air density reduction with increasing height is not significant for height of not more than 500 m [34,35]. Since atmospheric changes of pressure with increasing height of current high rise building height is not significant, the air density is assumed to be constants (incompressible flow). Moreover, the air inflow and outflow of high rise building depends on the HVAC system installed, where most of the HVAC system in typical buildings do not make significant changes to air properties to prevent the inadaptable condition. Thus, less fluctuation of atmospheric pressure and temperature can be assumed throughout all height range of the high rise building [36]. Since there is no extreme condition in the elevator shaft, the air within it is assumed as Newtonian fluid, which have a constant viscosity of 1.864×10^{-5}. Since temperature is not the main focus of this study, the thermal effect is neglected. Therefore, this study assumes an incompressible Newtonian fluid condition.

Eq. (1) shows the simplified Navier-Stokes equation for incompressible Newtonian fluid. The rate of change in air density is not included in the equation. Since this paper takes into account of air viscosity, the viscosity terms in Navier-Stokes equation is remained. Due to very low air viscosity, the velocity diffusion depends mainly on the diffusion of momentum. Despite, this very low viscosity is accounted via the application of no slip boundary conditions on the wall of shaft and car. Eq. (2) to (5) are the equations derived from Navier-Stokes equations based on the incompressible property. Eq. (2) shows the simplified continuity equation, while Eq. (3), (4), and (5) shows momentum equations in direction x, y and z respectively [37].

$$\rho\left[\frac{\partial v}{\partial t}+(v.\nabla)v\right]=-\nabla P+\rho g+\mu\nabla^2 v \quad (1)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial \rho}{\partial x} \tag{3}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho}\frac{\partial \rho}{\partial y} \tag{4}$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho}\frac{\partial \rho}{\partial z} \tag{5}$$

2.2 Methods
2.2.1 Elevator system model

This study focuses on car-shaft interaction which is main component of all types elevator system, excluding counter weight and other less significant components. As shown in Figure 1(a) and 1(b), the computational domain of elevator system which consists of elevator car (yellow) and shaft (blue) is constructed and meshed. The elevator car is a capsule with diameter of 1.6 m and height of 3.2 m, while the shaft is a rectangular box with dimension of 2.4 m X 7 m X 3.1 m. However, only symmetrical quarter section (z cut plane and x cut plane) of the 7 m long section of elevator system is constructed to represent the whole elevator system for simulation, in order to reduce the computational cost.

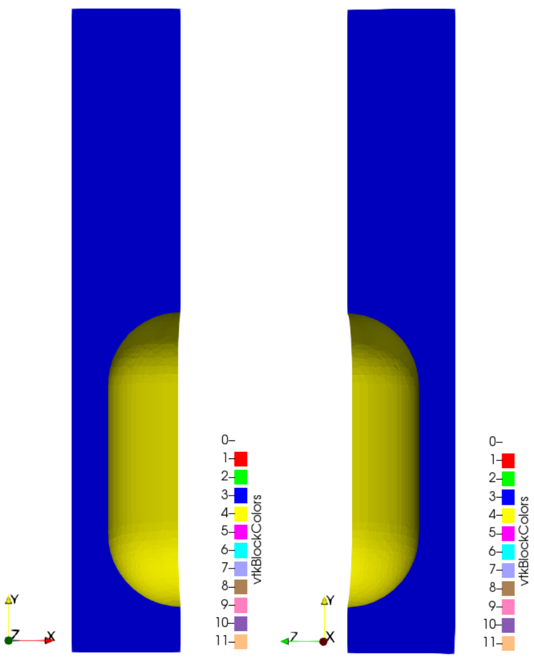

Fig. 1. (a) Symmetrical cut plane z (left) and cut plane x (right) of elevator model (surface view)

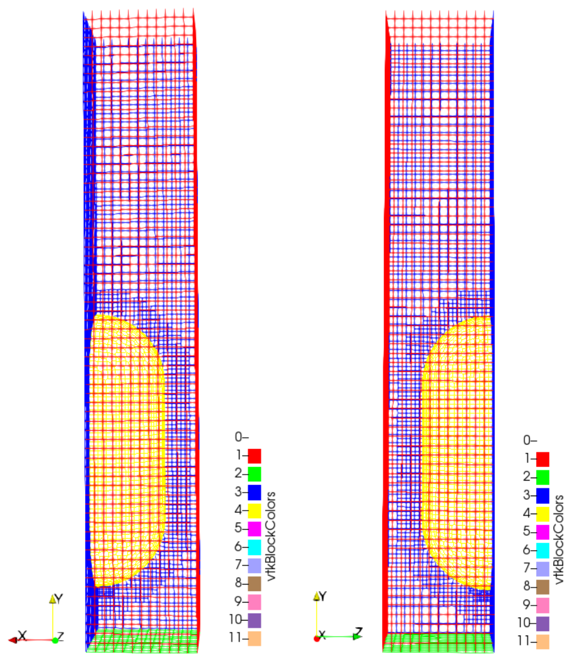

Fig. 1. (b) Back view (left) and side view (right) of symmetrical cut section of the elevator mesh (mesh view)

Symmetry boundary condition is set for the internal faces (yellow and blue) of the section, while no slip boundary condition was set for the external faces (red). The mesh composes of 23762 hexahedral cells and 4267 polyhedral cells. Moderate cell size is preferred over small and large cell size for this study, and the Reynolds Averaged Navier-Stokes (RANS) turbulence model is used, since this study focuses on the airflow behavior and pattern which influenced greatly by the wall effect of the car and shaft.

2.2.2 Computational approach

Finite volume method is used to solve the Euler equations and k epsilon turbulence model. Bounded Gauss vanLeer V, a 2^{nd} order scheme is chosen due to its stability and accuracy. Fixed mesh is used due to its high accuracy and efficiency.

PIMPLE algorithm is used to solve the numerical analysis. The initial condition of pressure is prescribed to solve the momentum equation, creating a pressure correction equation which adjusts the initial guessed pressure and velocity value. The numerical analysis is completed when the convergence criteria set is met.

Static elevator car and shaft, and moving air flowing at 20 m/s are used to represent the elevator car that is moving downward at 20 m/s in stationary air within the shaft [21,38]. To simulate this condition, the shaft bottom end is set as inlet with 20 m/s, top end as outlet with 20 m/s, and internal field as uniform 20 m/s. Elevator car rated speed of 8 m/s, 10 m/s, 17 m/s and 20 m/s are repeated using the same method. Since frictional force is accounted, no slip boundary condition is set to the shaft wall and car wall. The simulation time is up to 20 s to make sure the achievement of its equilibrium state.

The time step is calculated based on the car rated speed and the cell size, by using the formula shown in Eq. (6), with courant number of 1.

$$dt = \frac{(Co * dx)}{U} \tag{6}$$

where,
dt is the time step
Co is the courant number
dx is the cell size
U is the velocity (car rated speed)

2.2.3 Calculation of possibility of energy harvesting

Based on the studies on the possibility of energy harvesting using turbine mounted on the moving vehicle, the energy (from wind power) using typical small scale turbine is calculated using formula as shown in Eq. (7) [39,41].

$$P = 0.5C\rho AV^3 \tag{7}$$

where,

C is the coefficient of wind turbine performance [0.32 for typical small-scale wind energy portable turbine [32,33]] [0.593 for max efficiency (betz limit)] [42]].
ρ is the air density [1.2 kg/m^3 in Malaysia [43]].
A is the swept area of blade (m^2) [A= πr^2, radius 0.2 =0.13 for small-scale wind energy portable turbine [32]].
V is the air velocity [assume natural air velocity is 0 m/s when elevator is static, so V_{air} = $V_{elevator}$].

Since the significant high velocity and consistent airflow only observed at specific region when the car running at its rated speed, the calculation of energy harvesting only focuses on the specific region and time period when the car is running at its rated speed.

3. Results and Discussion

For all rated speed, the variation of air velocity, pressure and turbulence parameters (k, epsilon, nut) remain relatively constant over time when reached its steady state. Thus, the results are recorded starting from the steady state.

Figure 2 shows the air velocity simulation of downward movement of elevator car at the rated speed of (a) 8 m/s, (b) 10 m/s, (c) 17 m/s, and (d) 20 m/s. The velocity distribution obeys the law of energy conservation and shows the similar result as reported by past studies [20,28]. The average air velocity is observed to be directly proportional to the elevator car rated speed. The air velocity is distributed homogenously for rated speed of 8 m/s and 10 m/s, but heterogeneously for rated speed of 17 m/s and 20 m/s. The higher rated speed shows a larger size of high air velocity region. Similarly, this phenomenon was reported by previous study [38]. Since only car rated speed of 17 m/s and 20 m/s has a significant high air velocity region, they are more preferable to be used for wind power generation.

Table 1 shows the air velocity and potential wind power generation at high air velocity region for different elevator car rated speed. Both air velocity and potential wind power captured is directly proportional to the elevator car speed. Car rated speed of 20 m/s with largest high air velocity region with the maximum velocity of 38.84 m/s recorded the highest potential wind power captured, where the rated speed of 8 m/s with the smallest high air velocity region with the maximum velocity of 15.39 m/s recorded the lowest potential wind power captured.

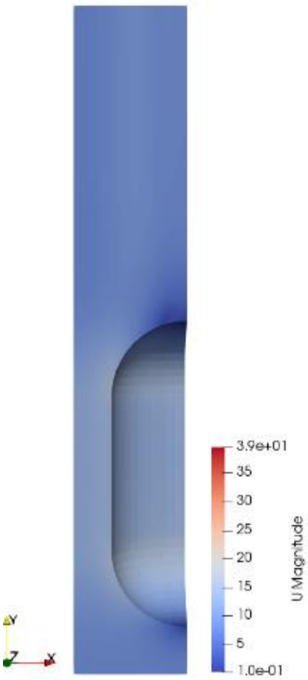

Fig. 2. (a) Velocity for rated speed of 8 m/s

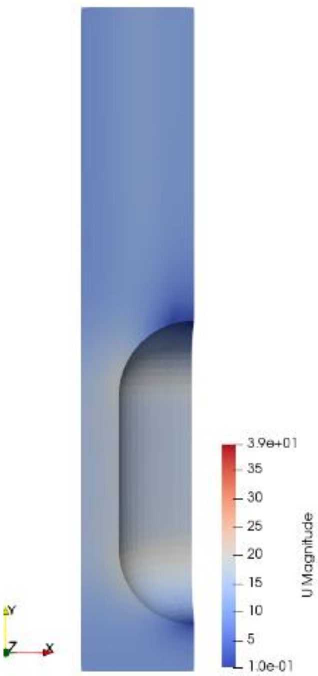

Fig. 2. (b) Velocity for rated speed of 10 m/s

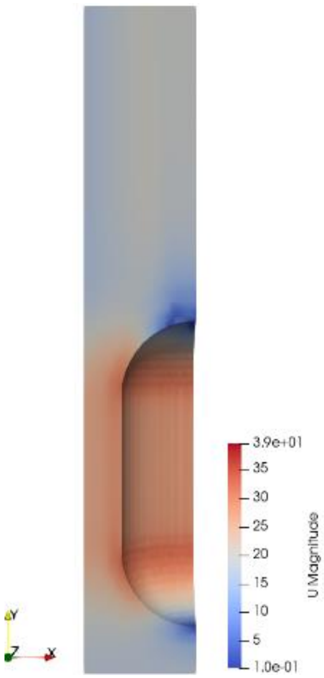

Fig. 2. (c) Velocity for rated speed of 17 m/s

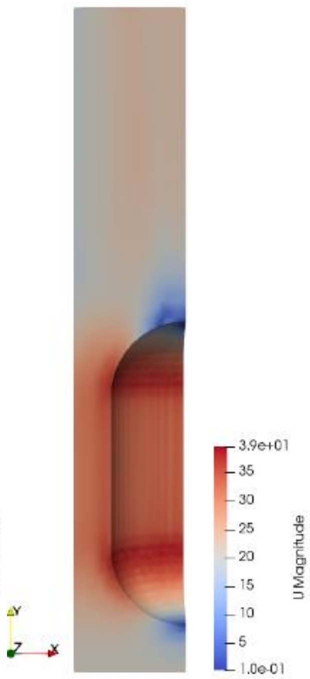

Fig. 2. (d) Velocity for rated speed of 20 m/s

Table 1
Air velocity and potential wind power generation at high air velocity region for different elevator car rated speed

Elevator rated velocity, U (m/s)	Air maximum velocity, V_{max} (m/s)	Air minimum velocity, V_{min} (m/s)	Air mean velocity, V_{mean} (m/s)	Potential wind power captured, P (W)
8	15.39	13.00	14.47	71.39
10	19.32	17.00	18.16	149.48
17	32.95	29.19	31.07	748.63
20	38.84	35.00	36.92	1256.12

Assumes C = 0.32 for small-scale wind energy portable turbine [32].

Figure 3 shows the turbulence at region between car and shaft wall caused by the drag effects of the car. Similarly, as reported by past studies, the upper side wall of the car which located at the wake region of the flow has a low velocity and high turbulence, indicating that the wind energy is low and inconsistent, so it is not a good spot for wind turbine placement [21,38]. The rest region has a relatively low turbulence.

Figure 4 and Figure 5 shows the air velocity contour for the case car rated speed of 17 m/s and 20 m/s respectively. The region highlighted with maroon colour near and at the lower side wall of the car is the spot with highest and consistent air velocity and low turbulence, which is the recommended spot for wind turbine to capture significant and consistent wind energy. The high air velocity for the case car rated speed of 17 m/s and 20 m/s range from 29.19 m/s to 32.95 m/s and 35.00 m/s to 38.84 m/s respectively.

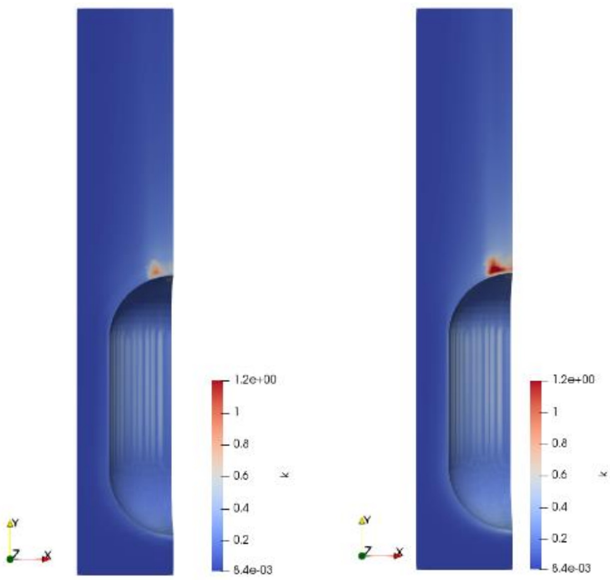

Fig. 3. Turbulence contour within the elevator system with the rated speed of 17 m/s (left) and 20 m/s (right)

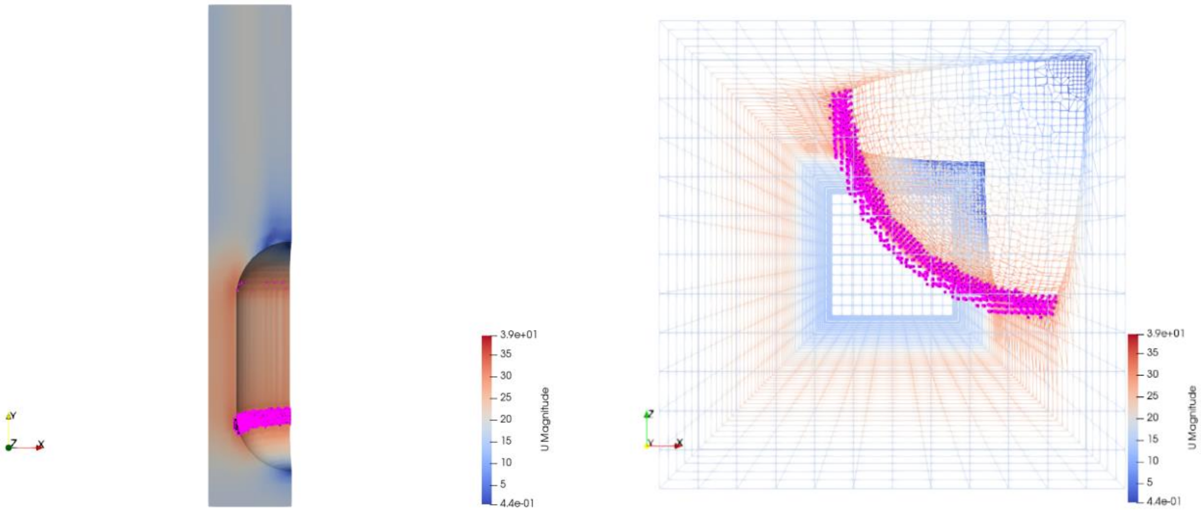

Fig. 4. The side view (left) and the bottom view (right) of the high air velocity and lower turbulence region highlighted in maroon for case rated car speed of 17 m/s

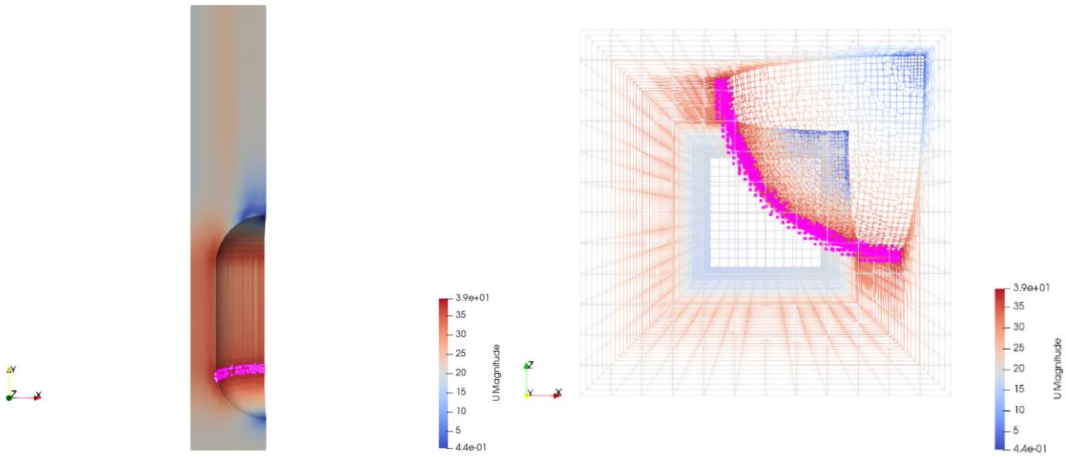

Fig. 5. The side view (left) and the bottom view (right) of the high air velocity and lower turbulence region highlighted in maroon for case rated car speed of 20 m/s

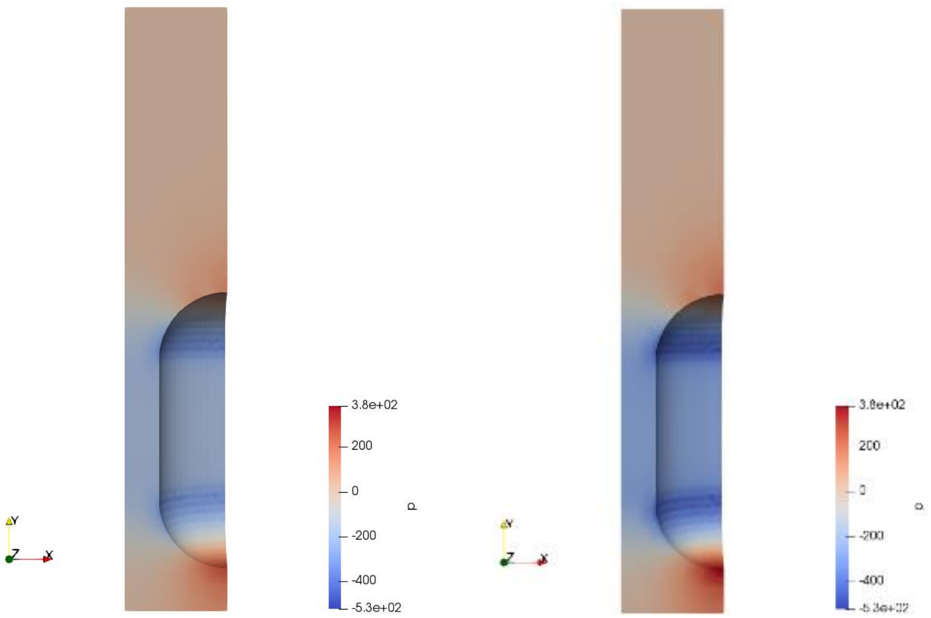

Fig. 6. Kinematic pressure for rated speed of 17 m/s (left) and 20 m/s (right)

Figure 6 compares the kinematic pressure within the elevator system with the rated speed of 17 m/s and 20 m/s (higher car rated speed case has a higher pressure differential which is 908.29 m^2s^{-2} (1089.94 Pa)). Similarly, Timo [38] mentioned that there is a larger pressure differential for the case with higher car rated speed.

Figure 7 shows the velocity and kinematic pressure of the air induced by the elevator car downward movement at 20 m/s. The minimum air velocity and maximum kinematic pressure at and around the car base wall are caused by the obstruction of incoming airflow by the car base facing directly to incoming airflow which is then separated, causing drag effect. The minimum air velocity at and around the car top wall is because it is protected from the direct airflow. The maximum air velocity of 38.84 m/s at the region between car lower side wall and shaft wall is larger than the elevator car's top speed of 20 m/s due to the concentration of high-velocity airflow. The similar observations were reported by previous studies [21,38]. The pressure shows a contrast phenomenon compared to that of the air velocity. This can be justified by Bernoulli's principle which states that when the high-velocity fluid (air) passing through the narrow region, its velocity increases, while its pressure drops [44,45]. The high-velocity point is the significant point to harvest the kinetic energy from the wind.

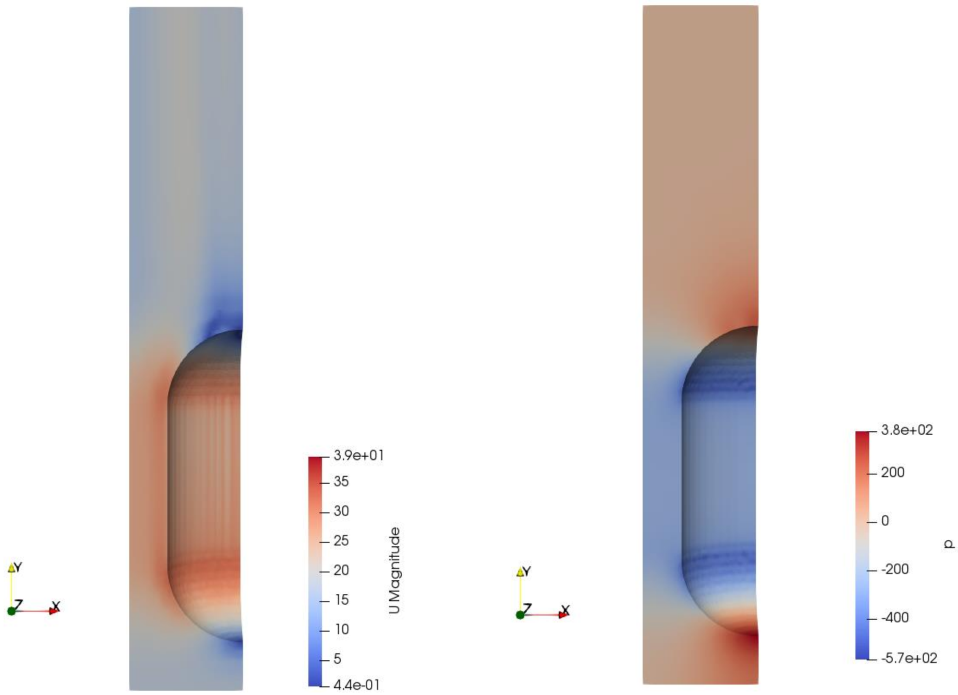

Fig. 7. Air velocity (left) and kinematic pressure (right) for car rated speed of 20 m/s

Based on the Table 2, from the wind power generation, potential electricity generation per complete trip is calculated. Generally, the air velocity and turbulent level are proportional to car rated speed. For the case with fixed time period of the elevator running at its rated speed, the highest car rated speed U = 20 m/s shows the highest capability to capture kinetic energy from the airflow. Interestingly, for the application in specific different height high rise building or shaft, the most generative car rated speed is different. For height 560 m, the potential electricity generation per complete trip increase with car rated speed. U = 20 m/s has the highest potential electricity generation per complete trip of 5.12 Wh. For height 400 m, the potential electricity generation per complete trip increase with car rated speed until U = 17 m/s which has the highest potential electricity generation per complete trip of 2.54 Wh and dropped to 2.32 Wh for U = 20 m/s. This is because car rated speed U = 20 m/s needs longer time for the car to reach its rated speed and thus shorter time for the car to run at rated speed. Therefore, for lower height shaft, a lower car rated speed is more effective as it achieves its rated speed faster and thus has a longer time of travel on its rated speed.

Table 2
Potential electricity generated per complete trip

Shaft height, h (m)	Elevator acceleration, a^a (m/s^2)	Car rated speed, U (m/s)	Time period car running at top speed, t (s)	Time period car running at top speed, t (h)	Potential electricity generated per complete trips, E (Wh)
560	1.5	8	64.67	0.01796	1.28
		10	49.32	0.01370	2.05
		17	21.62	6.0056E-3	4.49
		20	14.67	4.0750E-3	5.12
400	1.5	8	44.67	0.0124	0.89
		10	33.32	9.2600E-3	1.38
		17	12.2	3.3900E-3	2.54
		20	6.67	1.85E-3	2.32

[a] Maximum acceleration of existing high-speed elevator is used, a = 1.5 m/s.

4. Conclusion

The results reveal that the potential of the kinetic energy capturing from the moving elevator car, to generate electricity for the ancillary use of the system. In a fixed time period of the elevator running at its rated speed, car rated speed U = 20 m/s is reported to harvest the most kinetic energy in the airflow, which can be used for wind power generation of up to 1256.12 W. However, the appropriate elevator speed and shaft height should be adjusted accordingly to get the optimum match which has the longest time period for the car to run at its rated speed, in order to generate the most electricity. Moreover, the significant spot to capture induced airflow's kinetic energy needs to have low turbulence and high velocity.

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