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CFD SIMULATION OF PRESSURIZATION SYSTEM IN FIRE STAIRS WTC 6 BUILDING

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Abstract
Pressurization system in fire stairs is required for high-rise building for safety evacuation in fire attack. This paper has highlighted on the problem of WTC 6 high-rise building with 18 floors related to safety evacuation in fire attack. In real situation, the minimum air pressure (12.5 Pa) at closed condition and minimum air velocity (1 m/s) at open door chamber in fire stairs as stated in the SNI 03-6571-2001 requirements are not fulfilled by the WTC 6 high-rise building. Therefore, a CFD (Computational Fluid Dynamics) simulation has been used to overcome the problems. The CFD results show that volumetric air flow rate of 7.24 m^3/s injected to fire stairs in multiple injection system yielded pressure difference of 39.5–44.7 Pa and air velocity of 1.1–1.2 m/s. The CFD simulation implemented in real situation yields air pressure difference of 38.2 Pa in closed condition and air velocity in open door chamber of 1.16 m/s assumed to solve the problem.
Keywords: CFD simulation; fire stairs; pressurization system; safety evacuation.

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1. Introduction
With regard to safety evacuation in fire attack for high-rise building, Indonesian government launched some requirements in relation to creating facilities for safety solution that people may exit from the building fast and safe and go to assembly place [1]. The facilities include corridors, doors, smoke free lobby, fire stairs, and exit door. This article has discussed on a given part of those facilities namely as the fire stairs. The fire stairs in high-rise building are designed to save people in fire attack on the way directed to the exit door at ground level to open space.

Previous investigation reported that smoke assumed as the main cause in fire danger [2]. Because of that reason the facilities for safety evacuation has to emphasize on smoke free condition. In order to prevent smoke to enter fire stair chambers, a pressurization system is needed for fire stairs by generating a pressure in fire stair chambers higher than pressure in corridors. The effect of pressure difference causes air flows to outer space with certain velocity passing through openings of fire stair chambers during evacuation process.

The high-rise WTC 6 building with 18 floors is located in Jakarta. This building is provided with fire stairs layout as shown in Fig. 1. The fire protecting system in many old buildings in Jakarta does not follow the international regulations and latest government requirements, i.e., the SNI (Standar Nasional Indonesia) [3-4], and therefore, the pressurization system in fire stairs WTC 6 building with respect to air pressure distribution along fire stairs and corridor in closed door condition (minimum should be 12.5 Pa) and the air velocity at open door (minimum should be 1 m/s) not fulfilled the requirements. The real condition of fire stairs WTC 6 building yielded unmeasureable results with regard to the two variables of interest.

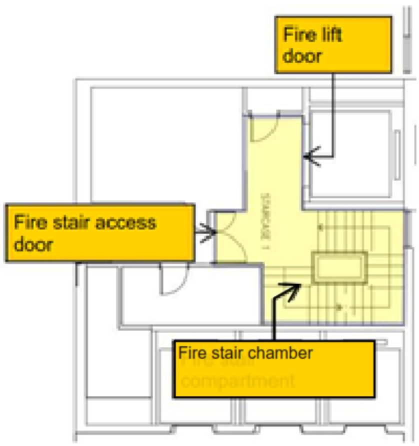

Fig. 1. Layout of fire stair chamber in WTC 6 building.

The objective of this study is to do the correction of fire protecting system in high-rise WTC 6 building applying CFD simulation in terms of air pressure distribution along fire stairs in closed condition and

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air velocity in open door chamber in order to meet the Government standard requirements.

Up to date, the simultaneous study on air pressure distribution along fire stairs in closed condition and air velocity in open door chamber for fire protecting system in high-rise building applying CFD simulation has not ever been reported. Previous investigations focused on smoke management system [2-3], and a modelling of fire protection management was reported [5], as well as other investigation more emphasized on testing, standardization and design of fire protecting system [6]. Therefore, this study gives a new insight with respect to fire management system for high-rise building.

1.1 Management of fire smoke in buildings.

All fire attack yields smoke that if it is not well managed it may spread over entire building or part of building that may destroy all things such as properties and even killing people. The smoke management system should be well designed to resist smoke flows into space for way out including corridors, protection area and any other zone [4]. The smoke management system should be in function during evacuation time in order to manage the protecting area. This system is designed to manage the smoke movement and to provide a safety zone and extra time for escaping from the building. The smoke may move from one chamber to adjacent chamber passing through air openings. Any hole in chamber wall is very susceptible to fire attack such apertures in windows, doors, ventilation and wall film [6].

The main reason that smoke may spread outside is due to pressure difference caused by several factors:

- Effect of chimney.
- Effect of fire temperature.
- Weather condition particularly wind and temperature.
- Mechanically air management system.

The building parts and facilitations such as wall, floor, door, damper, and stair well can be used simultaneously together with ventilation, and air conditioning in order to aid in the management of smoke movement, in other words, to arrange pressure difference [4].

There are two important factors to be noted in order to prevent smoke entering stair well, i.e.

a. Moderately large pressure difference operating on two barrier sides to manage smoke movement.
b. Air flow to manage smoke movement if the average air velocity large enough.

According to the guidance as mentioned in previous report [4], thus, the minimum pressure for a building should follow direction as shown in Table 1. By following the requirements as stated in Table 1, thus, the pressure difference of WTC 6 building with sprinkler provided should be 12.5 Pa.

Table 1. Estimation of minimum pressure difference following previous guidance [4].

No	Sprinkler system availability	Ceiling Height	Pressure difference (Pa)
1	Automatic sprinkler available	Low	12.5
2	Without sprinkler	2.7 m	25
3	Without sprinkler	4.5 m	35
4	Without sprinkler	6.4 m	45

On the other side, the maximum pressure difference is arranged for a value that is not exceeding the maximum value of open-door force as established for building regulations and human safety [7]. Table 2 listed the data of maximum pressure difference [4]. By considering close-door force listed in Table 2 as 6.3 Kgf for WTC 6 building, so the maximum pressure difference would be 55 Pa. This paper takes 50 Pa as a value between minimum and maximum to describe the pressure difference between fire stairs and outer space (corridors).

Table 2. Maximum pressure difference on doors at both sides following guidance [4].

No.	Door Closing Force (kgf)	Maximum Pressure Difference (Pa)
1	2.7	85
2	3.6	77.5
3	4.5	70
4	5.4	62.5
5	6.3	55

1.2 Pressurization system of stairs based on number of injection points.

According to reference [4] there are two criteria on the basis of number of injection points for stairs pressurization system, i.e.

A. Single injection system

This system has only one pressure source generally at the highest point (rooftop) or at the lowest point for the possibility of equipment installation to generate air pressure. The layout of this system is presented in Fig. 2.

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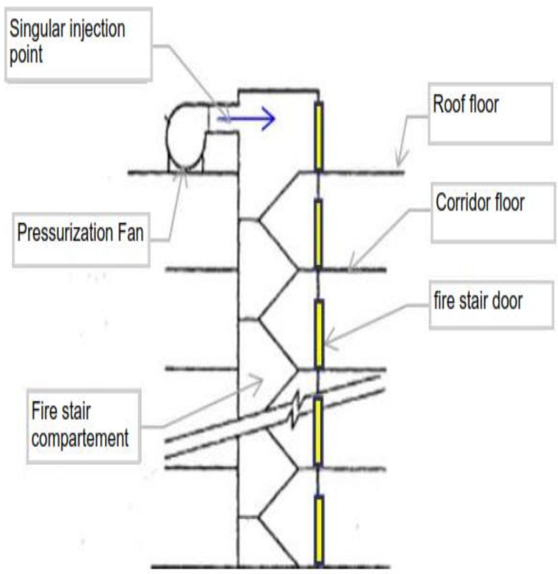

Fig. 2. Layout of single injection system for fire stairs.

B. Multiple injection system.

This system has several air injection sources to generate pressure generally spreading uniformly over all stairs at about same distance between injection points. The pressure source may come from one fan centralized or several fans which its air distribution directed to injection points aided by air chimney. The system layout is shown in Fig. 3.

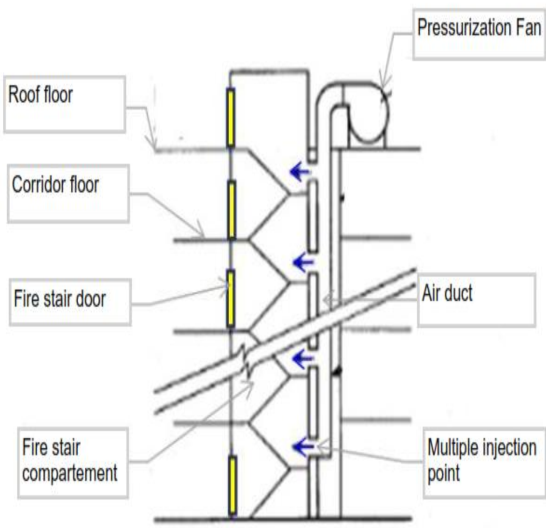

Fig. 3. Layout of multiple injection system for fire stairs.

1.3 CFD simulation for problems of fire stairs

CFD applications for fire attack can be divided into three groups, i.e., for research, design, and forensic. (i) For research, the CFD is capable to aid fire phenomenon fundamental elucidation. (ii) For design, the CFD is applied to estimate smoke and heat scattering from fire or fluid in real or planned building. (iii) For forensic, the CFD assists in real fire reconstruction [5].

Moreover, the CFD may simulate fluid movement for a condition using dynamic fluid calculations. The CFD may predict air movement in windy condition or fluid movement in the surrounding of a research object, either inside or outside the building. Previous investigation reported the usage of computer simulation in China to observe smoke movement and distribution in ventilation holes of a building applying pressurized system [8]. In addition, several countries investigated effects of leakage in fire stairs on air pressure [9 – 11]. Other report investigated open door condition for stairs following the guidance of American Society of Heating Refrigerating and Air-Conditioning Engineers [12].

2. Research Methodology

The flowchart of this study is illustrated in Fig. 4.

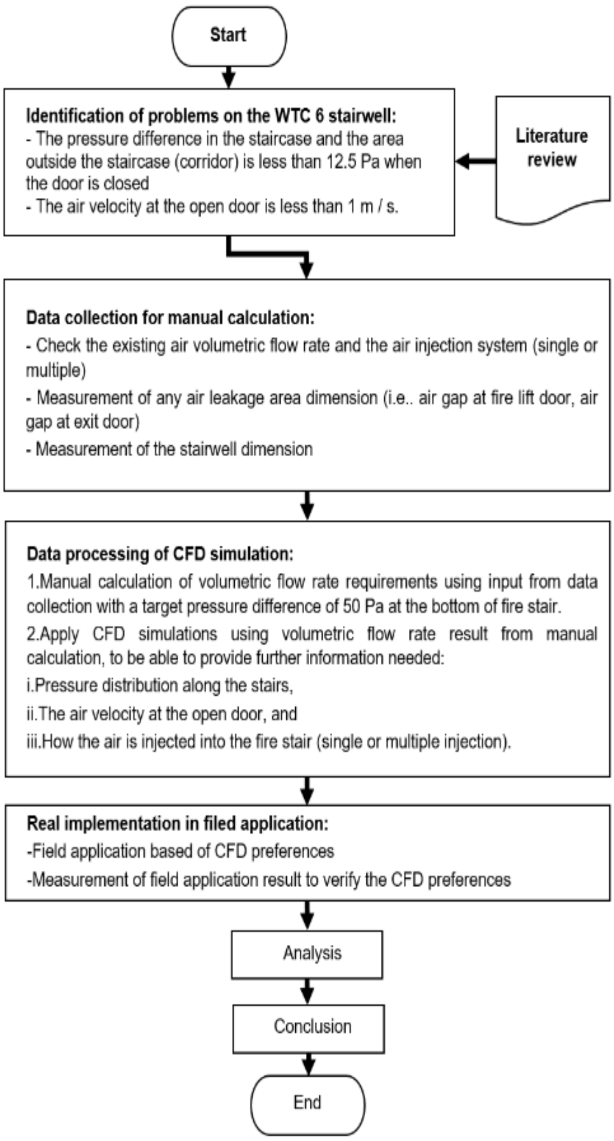

Fig. 4. Flow chart of this study

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The problem solving methods used in this study is divided into three stages, i.e.

1. Manual computation method.
2. CFD simulation method.
3. Results verification in real condition.

2.1 Manual computation method.

The manual calculation is to determine volumetric flow rate following the instruction of reference [13]. The result of manual calculation only yields the volumetric flowrate (m^3/s). The manual calculation can not give information on air pressure distribution along fire stair in closed condition, air velocity in open door chamber, as well as air distribution on fire stair using single or multiple injection system. Thus, those informations are only obtained from CFD simulation. Hence, the volumetric flowrate obtained from manual calculation will be used as the initial data in CFD simulation to give the information mentioned above. Fig. 4. clearly shows the correlation of manual calculation, CFD simulation, and real implementation.

The applied equation (1) is as followed:

$$Q = 0.559 N A_{sb} \left(\frac{\Delta p_{sbt}^{3/2} - \Delta p_{sbb}^{3/2}}{\Delta p_{sbt} - \Delta p_{sbb}} \right) \quad (1)$$

where,

$$\Delta p_{sbt} = \Delta p_{sbb} + \frac{By}{1+(A_{sb}/A_{bo})^2} \quad (2)$$

Notes:

Q = volumetric flow rate, m^3/s
N = number of floors
Δp_{sbt} = pressure difference from stairwell to building at stairwell top, Pa
Δp_{sbb} = pressure difference between stairwell and building at stairwell bottom, Pa
B = 3460(1/T_o - 1/T_s) at sea level standard pressure
y = distance above stairwell bottom, m
A_{sb} = flow area between stairwell and building (per floor)
= (Stairwell wall area x Average construction leakage fraction) + Door gap leakage, m^2
A_{bo} = flow area between building and outside (per floor)
= Building wall area x Average construction leakage fraction, m^2
T_o = temperature of outside air, K
T_s = temperature of stairwell air, K

2.2 CFD simulation

The CFD simulation has been conducted to estimate pressure and air velocity at fire stairs applying given variable of volumetric air flow rate. The ANSYS 17 software has been used for simulation of pressure and air velocity at fire stairs, while the Spaceclaim 17 for modeling of fire stairs building. The parameters listed in Table 3 are used for CFD simulation.

Table 3. *Matrix of parameters used for CFD simulation*

No.	Description	Numbers of Door Opened	ID	Notes
1	- Air volumetric flow rate existing (3.77 m3/s) - Single injection	0	1	For pressure difference parameter
		3	1.1	For air velocity parameter
2	- Air volumetric flow rate based on manual calculation (7.24 m^3/s) - Single injection	0	2	For pressure difference parameter
		3	2.1	For air velocity parameter
3	- Air volumetric flow rate based on manual calculation (7.24 m^3/s) - Multiple injection	0	3.0	For pressure difference parameter
		3	3.1	For air velocity parameter

The results of CFD simulation are used as reference for pressure distribution at close door and air velocity at open door condition. The simulation results are illustrated in Fig. 5 and Fig. 6.

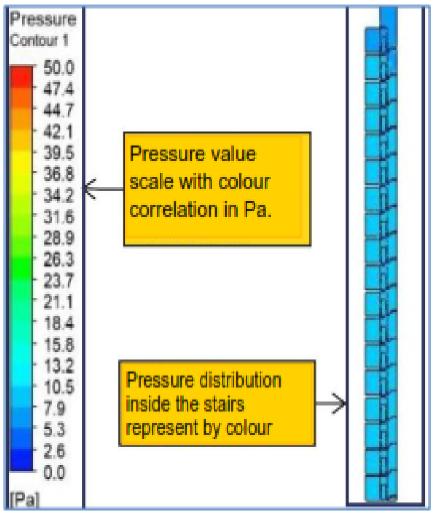

Fig. 5 Example of CFD simulation result for pressure distribution.

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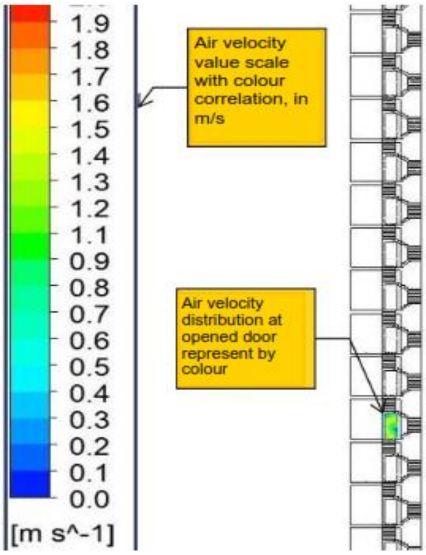

Fig. 6. Example of CFD simulation result for air velocity.

The simulation results show the pattern of pressure scattering in fire stairs and air velocity in open door that can be used as considerations for field application based on criteria as follows:

1. Pressure in the range of 12.5–55 Pa in close doors condition.
2. Air velocity in open door condition with minimum rate of 1 m/s with number of open doors determined by guidance [4], i.e., 10% x N +1 (N = number of floors). This study case is for 18 floors with three doors open.

3. Field verification

After finishing CFD simulation, the design will be applied in real field. The result of application will be repeated assayed. The repeated assayed is used as justification of validity of the solution implemented for fire stairs. The equipment applied in this study, i.e.

a. Anemometer hot wire type to measure air velocity of fire stairs in open door condition.
b. Pressure differential sensor to measure pressure difference between stairs chamber and outside corridor chamber.

3. Result

3.1 Manual computation

The manual calculation applied building data applying the given formula as follows:

1. Building data in real condition.
2. Opening at fire lift door 2 mm [14].
3. Opening at exit door 1.3 mm.
4. Average construction leakage fraction 0.17 x 10^{-3} [13].
5. The target of pressure difference between fire stairs and corridor (50 Pa).

Equation (1) was applied to determine air flow rate for fire stairs as instruction [13] to obtain the target of pressure difference (50 Pa) gives results as follows (Table 4):

Table 4. *Result of manual calculation related to pressure difference and air flow rate.*

Data	Value	Unit
Δp_{sbb}	50	Pa
T_o	33	ºC
T_s	35	ºC
N	18	floors
y	72	m
B	0.073	Pa/m
A_{sb}	0.0661	m^2
A_{bo}	0.89148	m^2
Δp_{sbt}	55.26	Pa
Result		
Q (Air Flowrate)	7.24	m^3/s

Table 4 shows the result of manual computation to obtain the maximum pressure difference at bottom of stair (50 Pa) as the target and the air flow rate (Q) is found to be 7.24 m^3/s. This value of air flow rate will be used in CFD simulation to give information on air pressure distribution along fire stairs in closed condition, air velocity (wind rate) in open door, and the way of air injection (single or multiple injection).

3.2 CFD simulation.

The result of manual calculation for air flow rate following instruction [13] and air flow rate obtained from real measurement of fire stairs will be used in CFD simulation applying matrix data listed in Table 3. The results of CFD simulation are illustrated in Fig. 7–12.

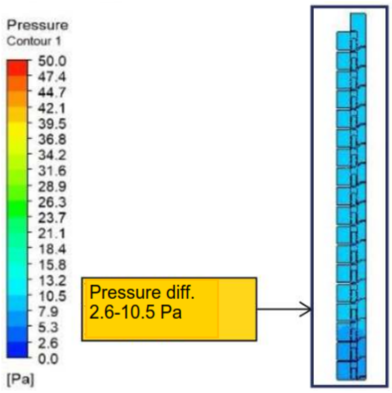

Fig. 7. CFD simulation (code 1.0); air flow rate 3.77 m^3/s; close door; single injection; pressure difference found to be 2.6–10.5 Pa

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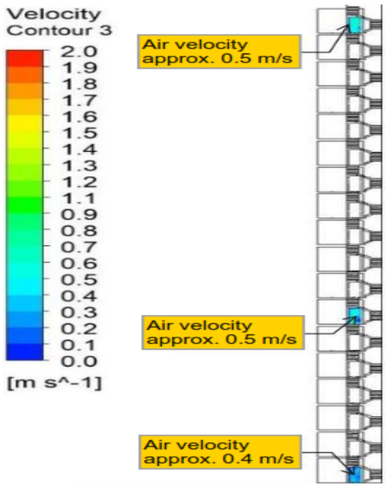

Fig. 8. CFD simulation (code 1.1); air flow rate 3.77 m^3/s; single injection; three open door; air velocity found to be 0.4–0.5 m/s.

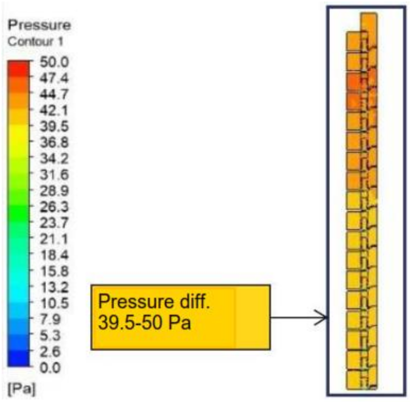

Fig. 9. CFD simulation (code 2.0); air flow rate 7.24 m^3/s; close door; single injection; pressure difference found to be 39.5 – 50 Pa.

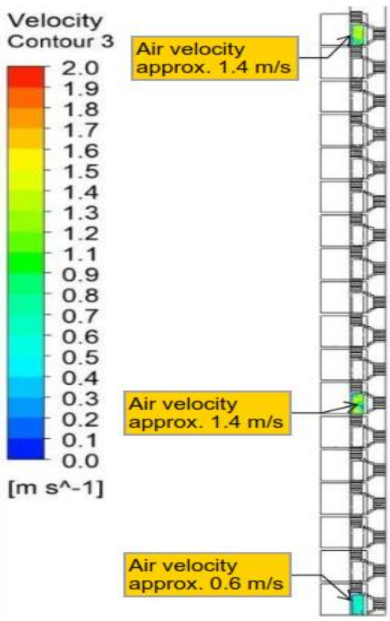

Fig.10. CFD simulation (code 2.1); air flow rate 7.24 m^3/s; single injection; three open door; air velocity found to be 0.6–1.4 m/s.

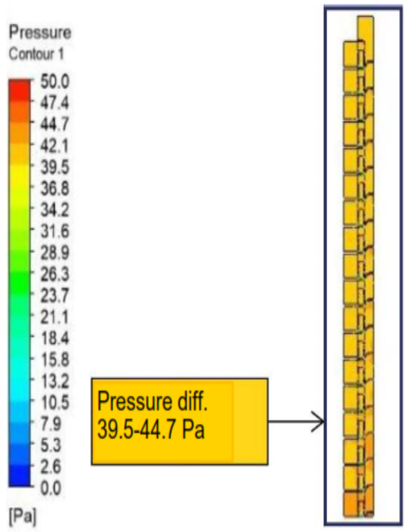

Fig. 11. CFD simulation (code 3.0); air flow rate 7.24 m^3/s; close door; multiple injection; pressure difference found to be 39.5–44.7 Pa.

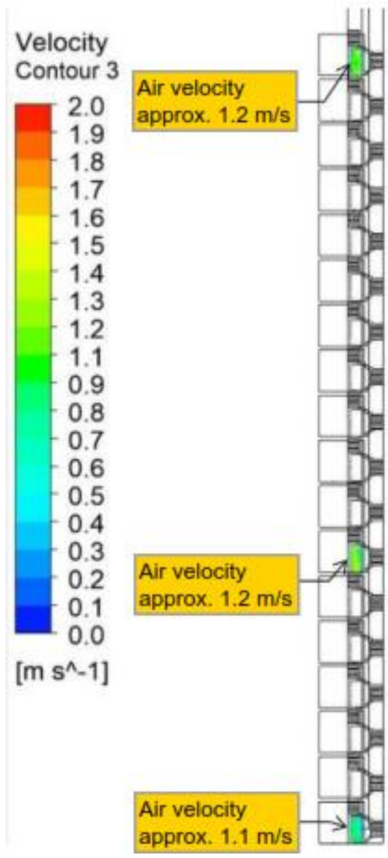

Fig. 12. CFD simulation (code 3.1); air flow rate 7.24 m^3/s; three open door; multiple injection; air velocity found to be 1.1–1.2 m/s.

Table 5 lists the summary of CFD simulations illustrated in Fig. 7–12.

Table 5. Results of CFD simulations.

No	Description	Result	Notes
1	- Air volumetric flow rate existing (3.77 m^3/s) - Singular injection	Diff. Press. 2.6-10.5 Pa	<12.5Pa
		Air velocity 0.4-0.5 m/s	<1 m/s
2	- Air volumetric flow rate based on manual calculation (7.24 m^3/s) - Singular injection	Diff. Press. 39.5-50 Pa	>12.5Pa
		Air velocity 0.6-1.4 m/s	<1 m/s
3	- Air volumetric flow rate based on manual calculation (7.24 m^3/s) - Multiple injection	Diff. Press. 39.5 – 44.7 Pa	>12.5Pa
		Air velocity 1.1-1.2 m/s	>1 m/s)

Results of CFD simulation can be presented in other form of illustrations (Fig. 13 dan Fig. 14).

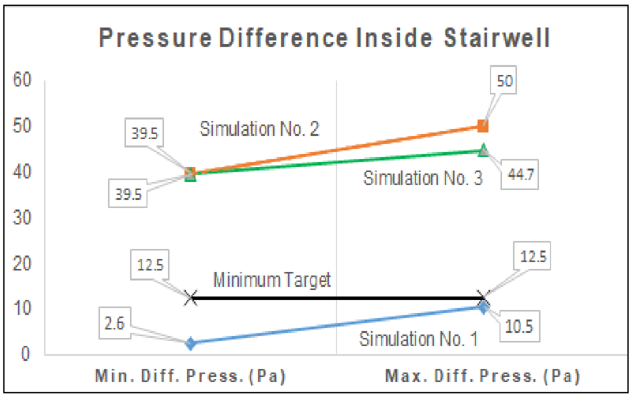

Fig. 13. Results of three CFD simulations for pressure difference toward minimum target 12.5 Pa.

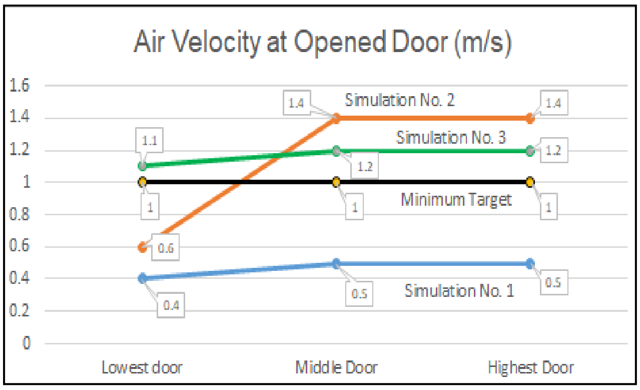

Fig. 14. Results of three CFD simulations for air velocity toward minimum target 1 m/s.

The results of CFD simulation show as follows:

Simulation no. 1 using real situation with volumetric air flow rate of 3.77 m^3/s and single injection yielded air pressure distribution of 2.6–10.5 Pa lower than minimum standard (12.5 Pa) and air velocity of 0.4–0.5 m/s lower than minimum standar (1 m/s).

Simulation no. 2 using real situation with volumetric air flow rate of 7.24 m^3/s and single injection yielded air pressure distribution of 39.5-50 Pa fulfilled the minimum standard (12.5 Pa) and air velocity of 0.6–1.4 m/s assumed not yet fulfilled the minimum standard (1 m/s).

Simulation no. 3 using real situation with volumetric air flow rate of 7.24 m^3/s and multiple injection yielded pressure distribution of 39.5–44.7 Pa fulfilled the minimum standard (12.5 Pa) and air velocity of 1.1–1.2 m/s fulfilled the minimum standard (1 m/s).

Therefore, this study tends to take the simulation no. 3 that meets the standard requirements.

In addition, the simulation no. 3 using multiple injection system gives more advantage with respect to more uniform distribution of air pressure and air velocity along fire stairs in high-rise building.

3.3 Field verification

Results of field verification implemented in real condition have been conducted by applying fan installed with capacity of 7.24 m^3/s with multiple injection by using air-duct installing in fire stairs chamber. The layout is shown in Fig. 15.

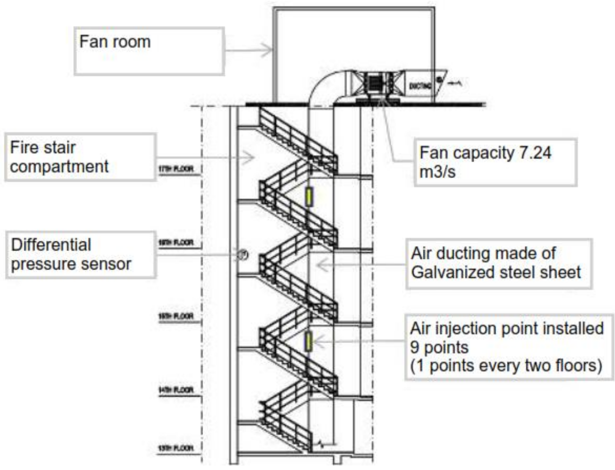

Fig. 15. Layout of pressurized system design for fire stairs WTC 6 building.

After the pressurization design installed in WTC 6 building, the results of measurement show the pressure difference between fire stairs chamber and corridor is found to be 38.2 Pa as shown in Fig. 16. The air velocity at three open door is found to be 1.16 m/s as shown in Fig. 17. The results justified the CFD simulation is useful for real implementation.

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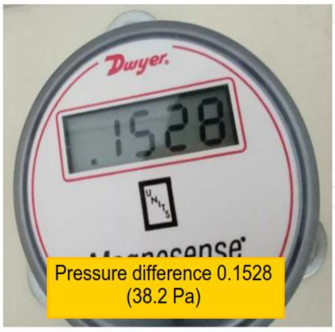

Fig. 16. The result of pressure measurement in fire stairs at close door (38.2 Pa).

Fig. 17. The result of air velocity measurement in fire stairs (1.16 m/s).

The study shows that the problem of fire stairs in WTC 6 building addressing to pressure difference between fire stair chamber and outside corridors and air velocity in three open doors can be solved by CFD simulation to fulfill the SNI requirements [4].

4. Conclusions

The CFD simulation is successfully used to solve problem in fire stairs WTC 6 building that gives prediction of volumetric air flow rate of 7.24 m^3/s applying multiple injection system. Applying the given volumetric air flow rate the study obtained air pressure distribution of 38.2 Pa in close door condition and air velocity of 1.16 m/s in open door chamber that fulfilled the minimum requirements (12.5 Pa and 1 m/s). The results show a novelty of this investigation.

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